TROPOSPHERIC AEROSOLS:

THE WILD CARD IN RADIATIVE FORCING OF CLIMATE CHANGE

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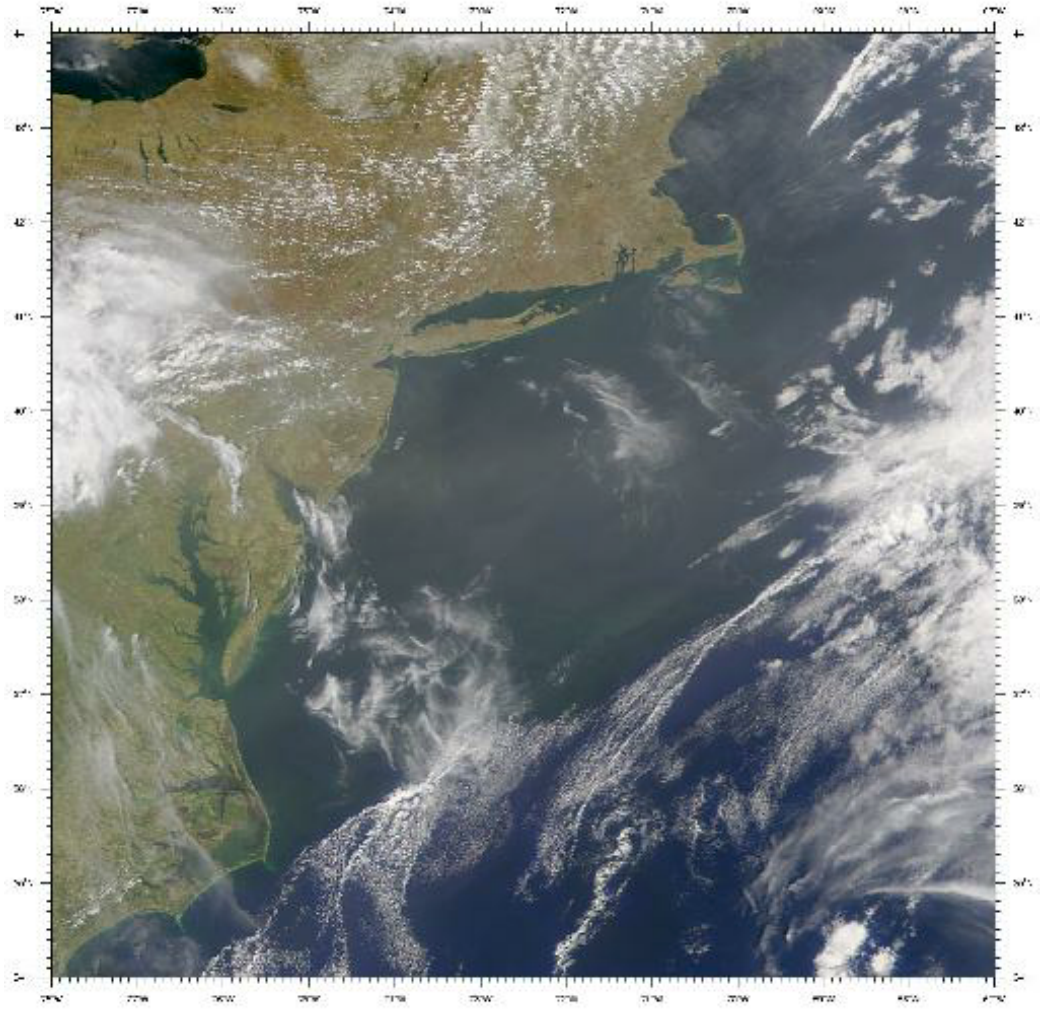
http://www.ecd.bnl.gov/steve/schwartz.html

AEROSOL: A suspension of particles in air



2001-04-22-17:28

SeaWiFS Project, NASA/Goddard Space Flight Center, and ORBIMAGE

Atmospheric aerosols may result from primary emissions (dust, smoke) or from gas to particle conversion in the atmosphere (haze, smog).

KEY POINTS OF THIS PRESENTATION

- ***Radiative forcing of climate change by anthropogenic aerosols is substantial in the context of other forcings of climate change over the industrial period.***

  Cooling forcings of ***tens of watts per square meter*** have been demonstrated ***locally and instantaneously***.

  Global annual mean forcings of -1 to -3 W m^{-2} are plausible given present understanding.

- ***Uncertainty in radiative forcing of climate change by anthropogenic aerosols is the greatest source of uncertainty in forcing of climate change.***

  This uncertainty precludes:

  - ***Evaluation of models*** of climate change
  - ***Inference of climate sensitivity*** from temperature changes over the industrial period.
  - ***Informed policy making*** on greenhouse gases.

cont'd . . .

KEY POINTS OF THIS PRESENTATION (*cont'd*)

- ***Confidence in present estimates of global sensitivity to climate change may be greatly overstated.***

- ***Radiative forcing by aerosols cannot be an effective means of counteracting forcing by greenhouse gases.***

  Aerosols are short lived in the atmosphere (days).

  Greenhouse gases are long-lived (decades)

  In the long run GHGs will win.

OUTLINE OF THIS PRESENTATION

- ***Forcing and climate sensitivity***
- ***Mechanisms of radiative forcing by aerosols***
  Direct
  Indirect (via clouds)
- ***Magnitudes of radiative forcing by aerosols***
  Local and instantaneous
  Global
- ***Uncertainties in radiative forcing by aerosols***
  Causes
  Magnitudes
- ***Implications of these uncertainties***
- ***What must be done to reduce these uncertainties?***

TOP-LEVEL QUESTION IN CLIMATE CHANGE SCIENCE

- ***How much will the global mean temperature change?***

$$\Delta T = \lambda F$$

where F is the ***forcing*** and λ is the ***climate sensitivity***.

- A ***forcing*** is a change in a radiative flux component, W m^{-2}.
- Forcings are thought to be ***additive*** and ***fungible***.

- ***What is Earth's climate sensitivity?***
  - ***National Academy Report (Charney, 1979):***

"We estimate the most probable global warming for a doubling of CO_2 to be ***near 3 degrees C***, with a probable error of ***plus or minus 1.5 degrees***.

- ***Intergovernmental Panel on Climate Change (IPCC, 2001):***

"Climate sensitivity [to CO_2 doubling] is likely to be in the range ***1.5 to 4.5˚C***.

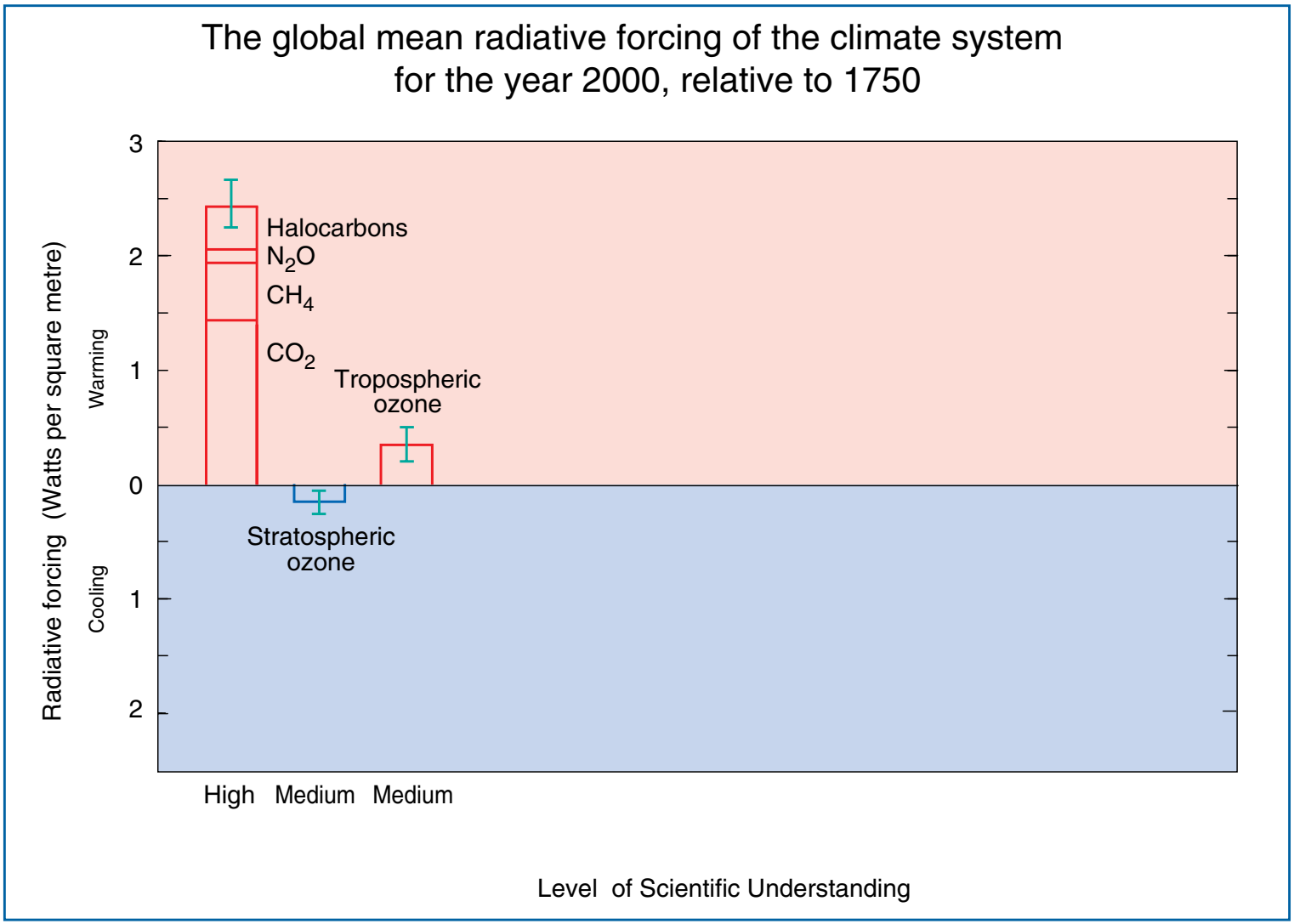
HOW CAN CLIMATE SENSITIVITY BE DETERMINED?

Climate sensitivity $\lambda = \Delta T / F$

- ***Climate models*** evaluated by performance on prior climate change and/or
- ***Empirical determination*** from prior climate change
- Either way, ΔT and F must be determined with sufficiently small uncertainty to yield an uncertainty in λ that is useful for informed decision making.
- Present generally accepted uncertainty in λ (1.5 to 4.5˚C) — a factor of 3 — is not very useful for policy planning purposes.
- ***Uncertainty may be much greater!***

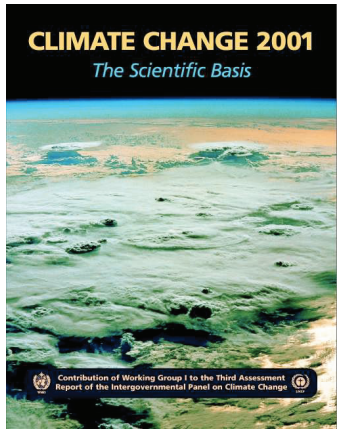
RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)

Greenhouse gases only



Summary for Policymakers

A Report of Working Group I of the Intergovernmental Panel on Climate Change



AEROSOL INFLUENCES ON RADIATION BUDGET AND CLIMATE

Direct Effect (Cloud-free sky)

Light scattering -- Cooling influence

Light absorption -- Warming influence, depending on surface

Indirect Effects (Aerosols influence cloud properties)

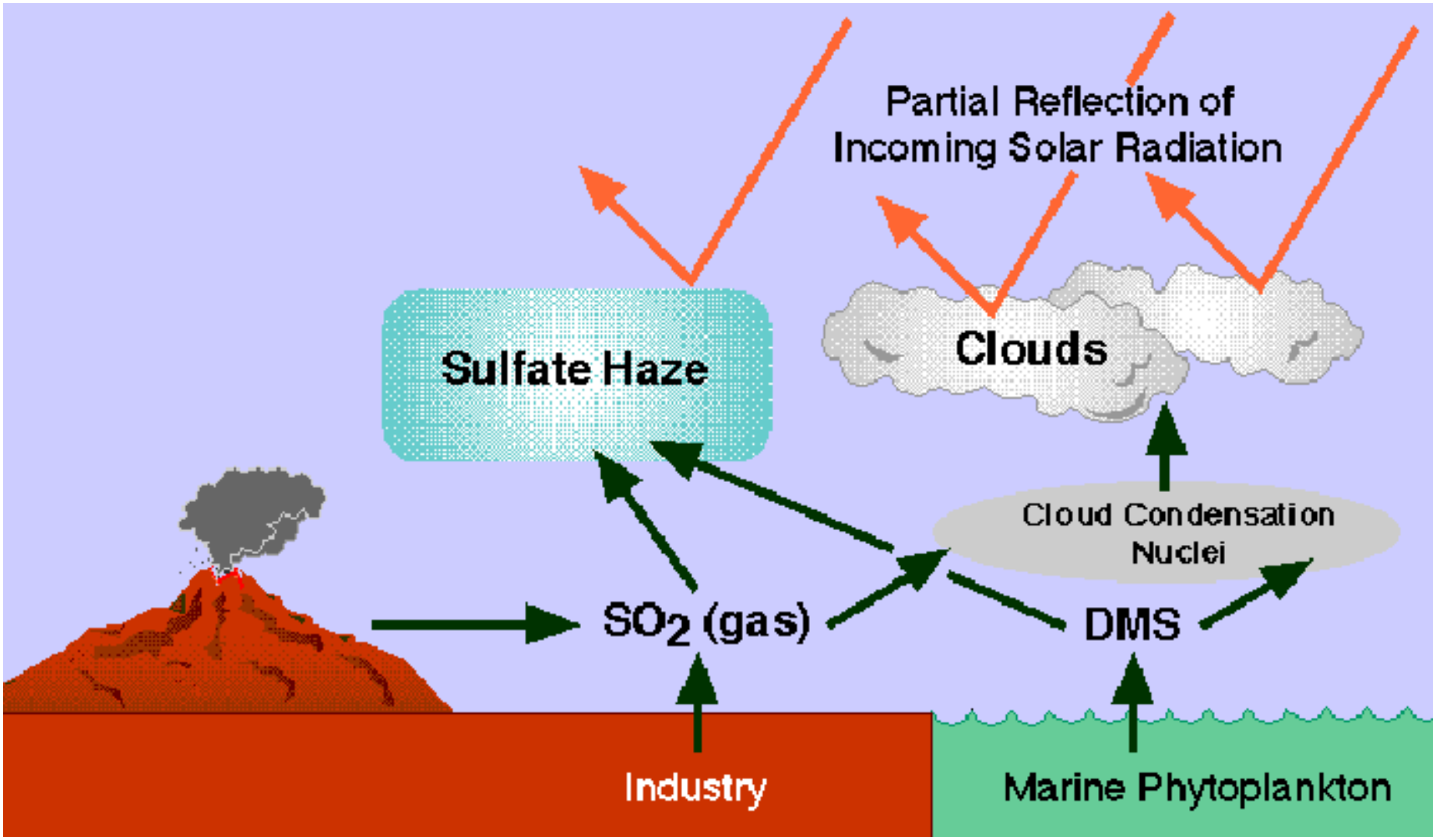
More droplets -- Brighter clouds (Twomey)

More droplets -- Enhanced cloud lifetime (Albrecht)

Semi-Direct Effect

Absorbing aerosol heats air and evaporates clouds

CLIMATE FORCING BY SULFATE AEROSOL



Forcing is the change in absorbed solar irradiance due to the presence of the aerosol.

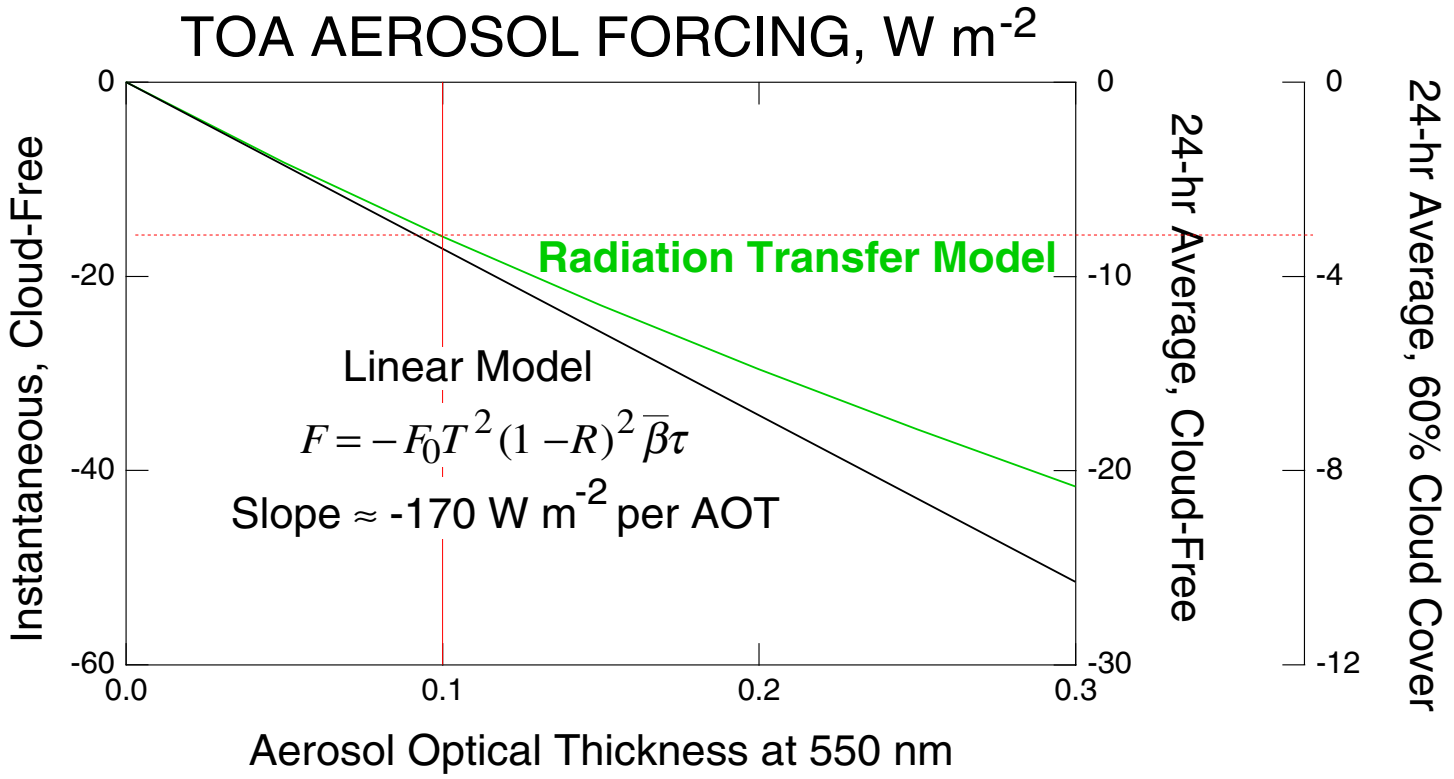
DIRECT EFFECT

DIRECT AEROSOL FORCING AT TOP OF ATMOSPHERE

Dependence on Aerosol Optical Thickness

Comparison of Linear Formula and Radiation Transfer Model

Particle radius r = 85 nm; surface reflectance R = 0.15; single scatter albedo ω_0 = 1.

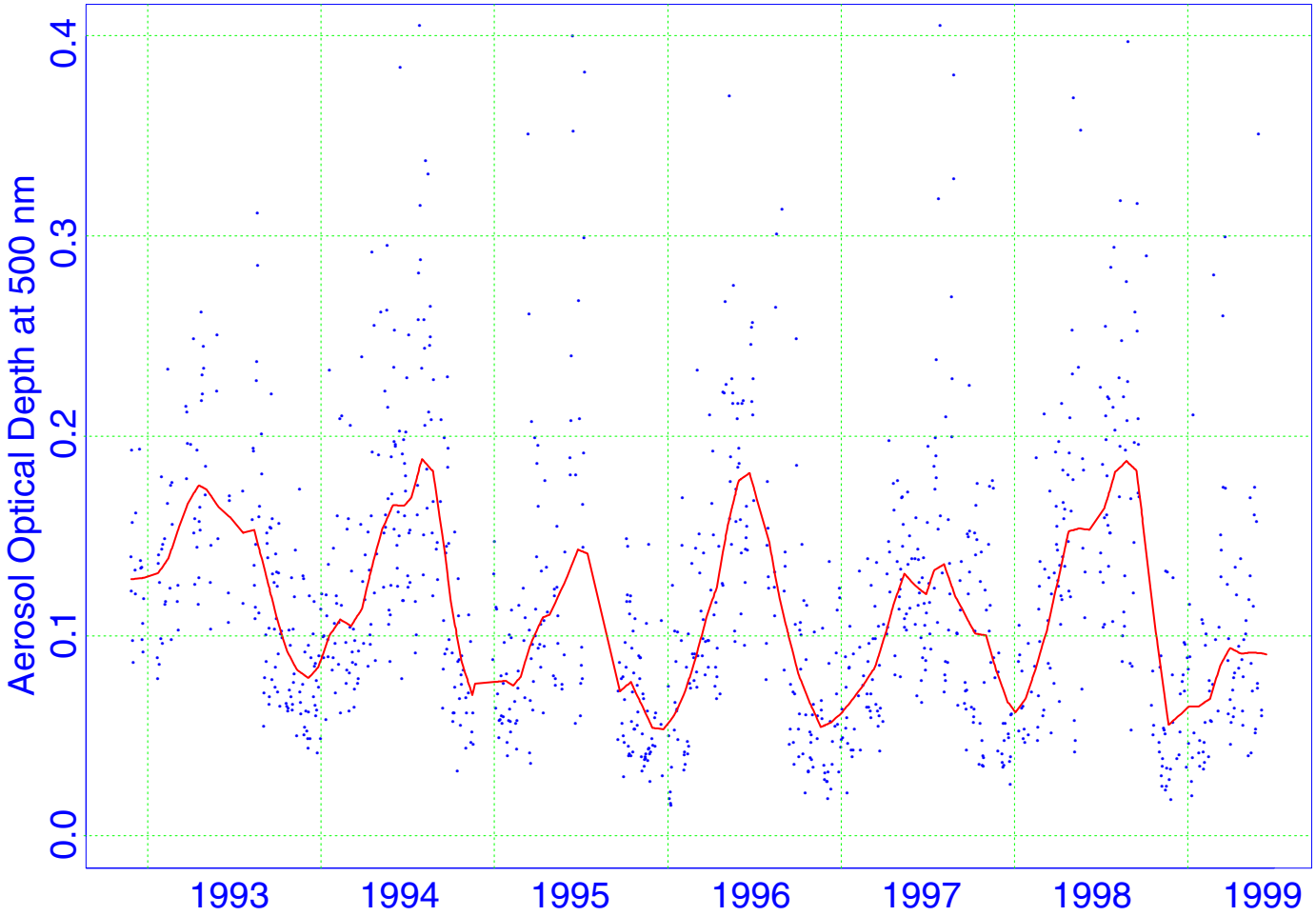


Global-average AOT 0.1 corresponds to global-average forcing -3.2 W m^{-2}.

AEROSOL OPTICAL DEPTH

Determined by Sunphotometry

North Central Oklahoma - Daily Average



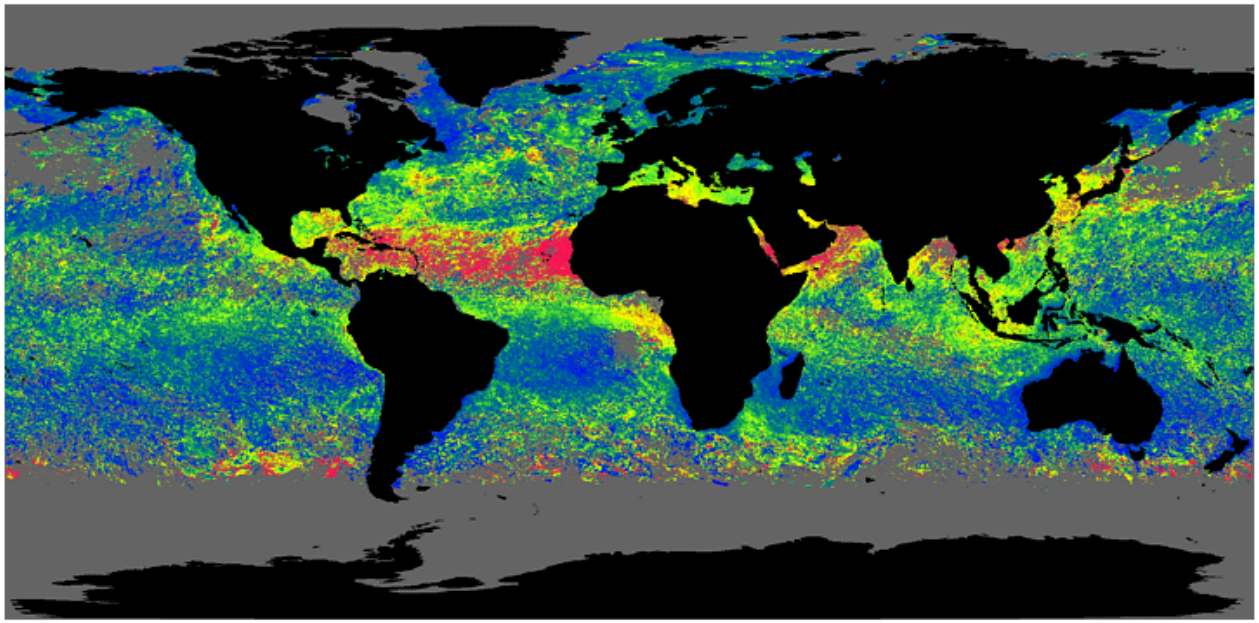
J. Michalsky et al., JGR, 2001

MONTHLY AVERAGE AEROSOL JUNE 1997

Polder radiometer on Adeos satellite

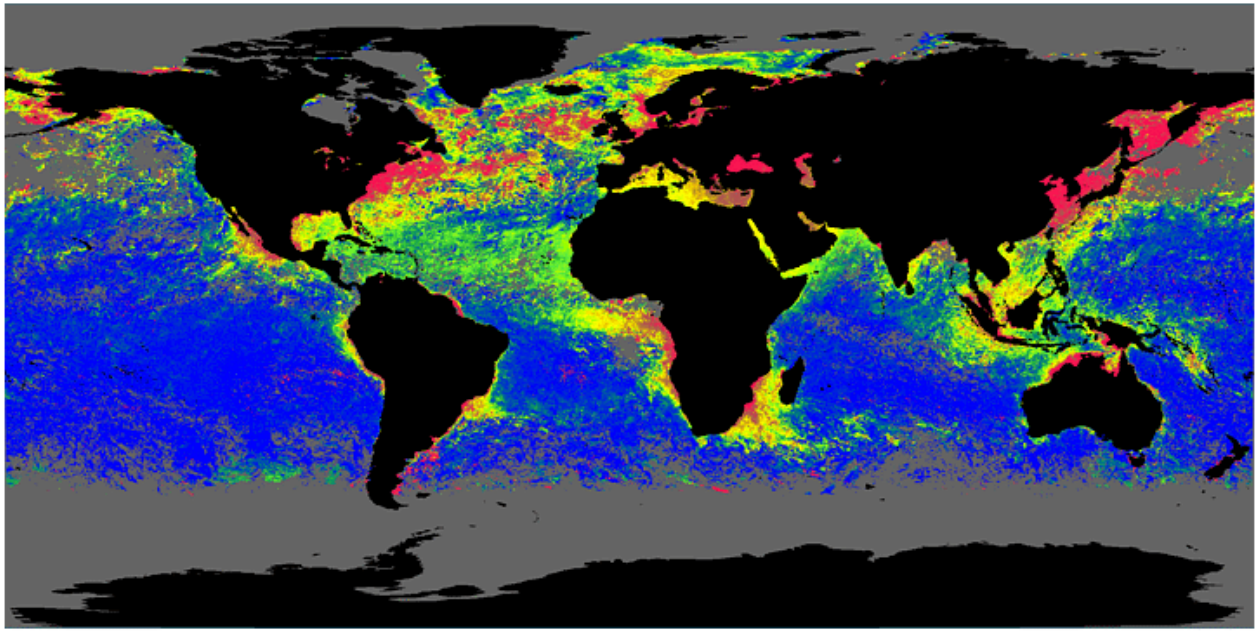
Optical Thickness τ

$\lambda = 865$ nm



Ångström Exponent α

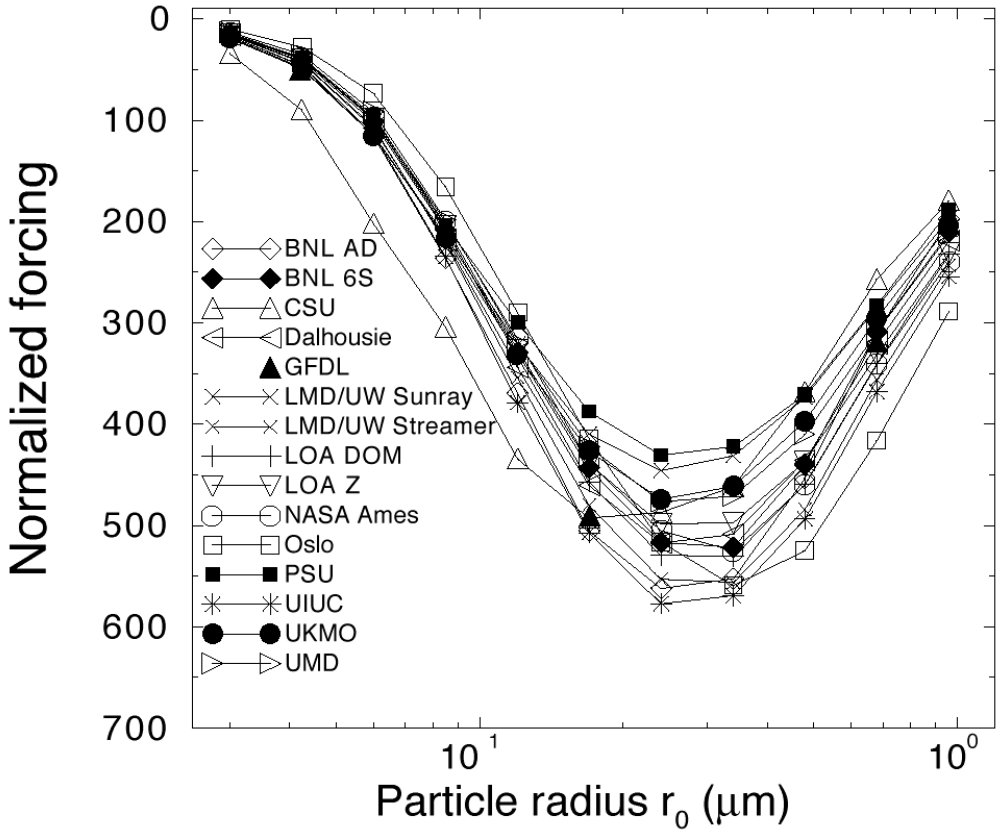
$$\alpha = -d \ln \tau / d \ln \lambda$$



INTERCOMPARISON OF BROADBAND SHORTWAVE FORCING BY AMMONIUM SULFATE AEROSOL

Normalized global-average forcing: W m^{-2} / g(SO_4^{2-}) m^{-2} or W /g(SO_4^{2-})

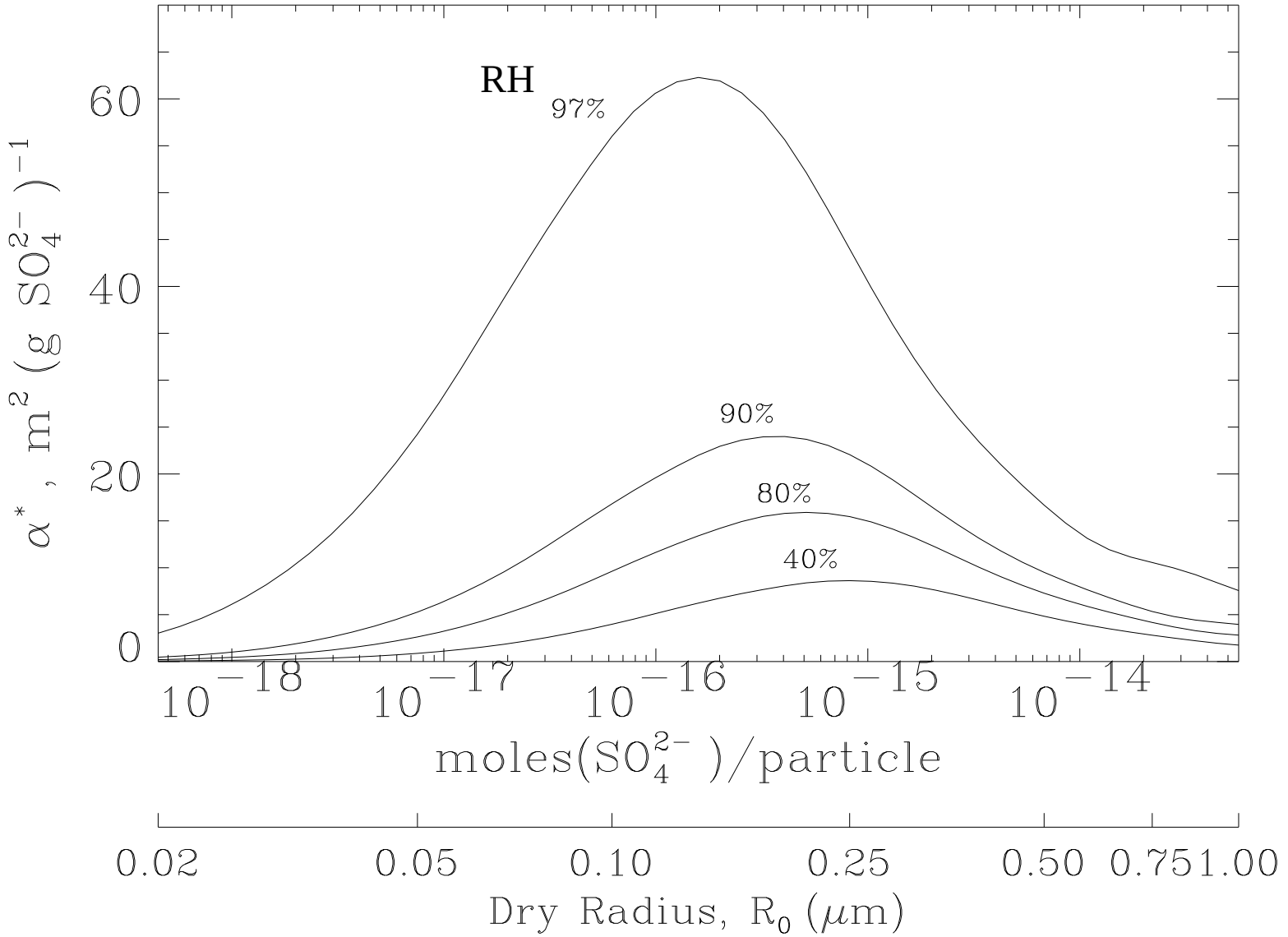
Aerosol optical depth 0.2; surface albedo 0.15



Standard deviation ~8% for 15 models at radius ~ 200 nm.

Boucher, Schwartz and 28 co-authors, JGR, 1998

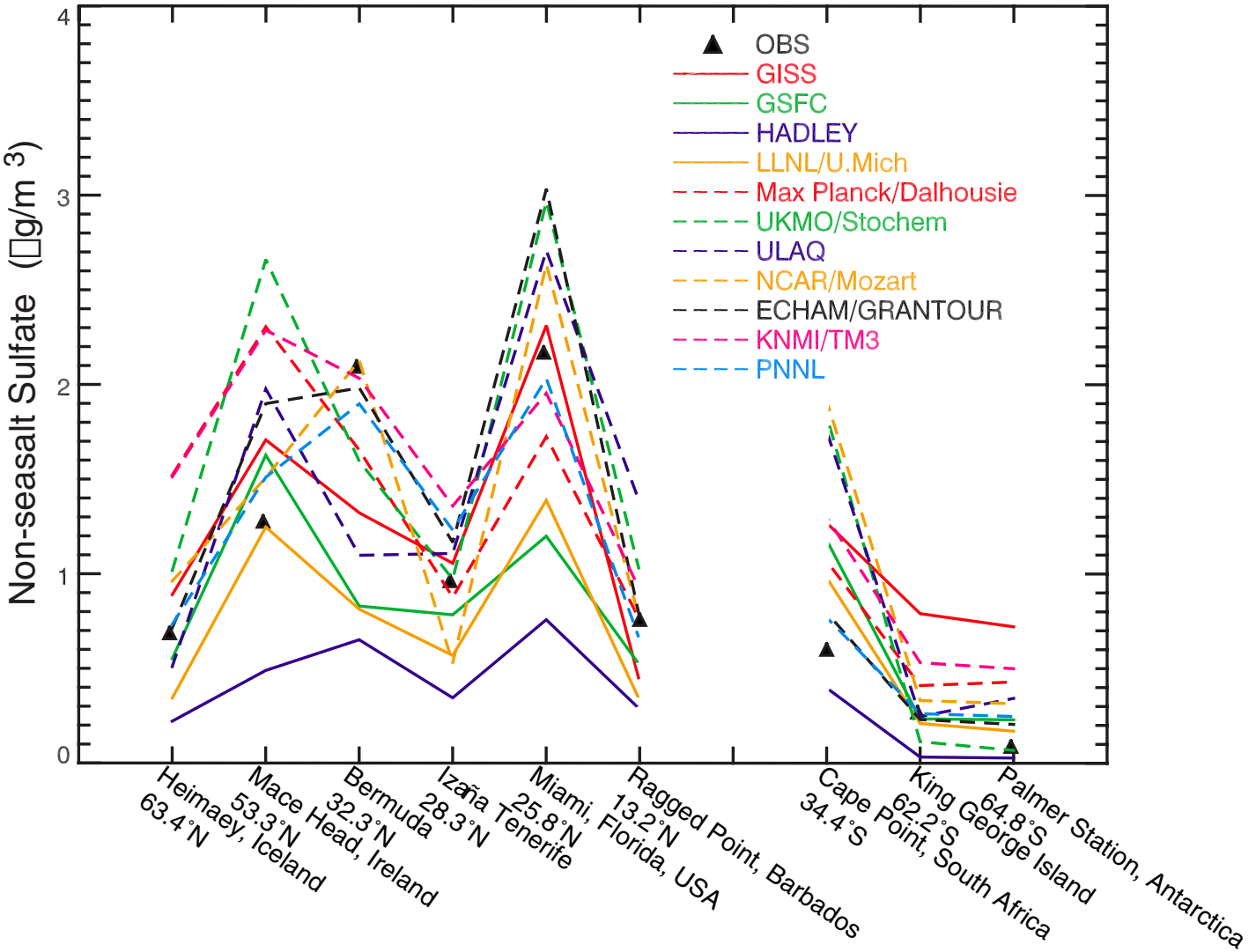
LIGHT SCATTERING EFFICIENCY OF $(NH_4)_2SO_4$ DEPENDENCE ON PARTICLE SIZE AND RH



Nemesure,Wagener & Schwartz, JGR, 1995

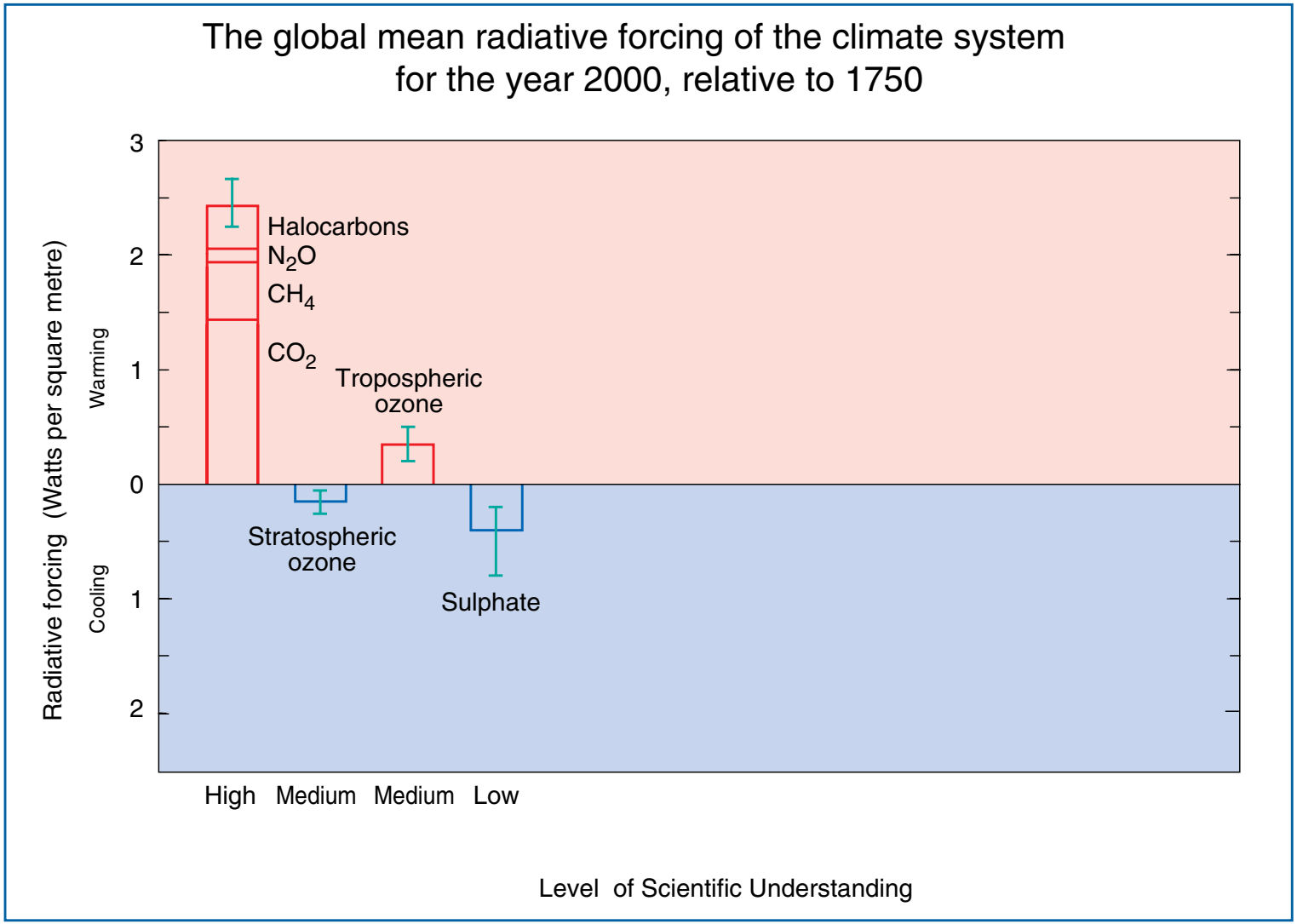
SULFATE MODEL INTERCOMPARISON

Annual average non-seasalt sulfate in 11 chemical transport models and comparison with observations at nine stations



Penner et al., IPCC, 2001

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
GHG's and sulfate aerosol direct effects



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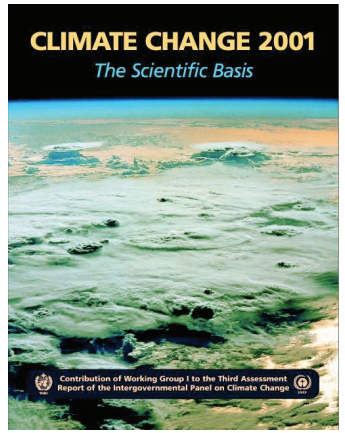

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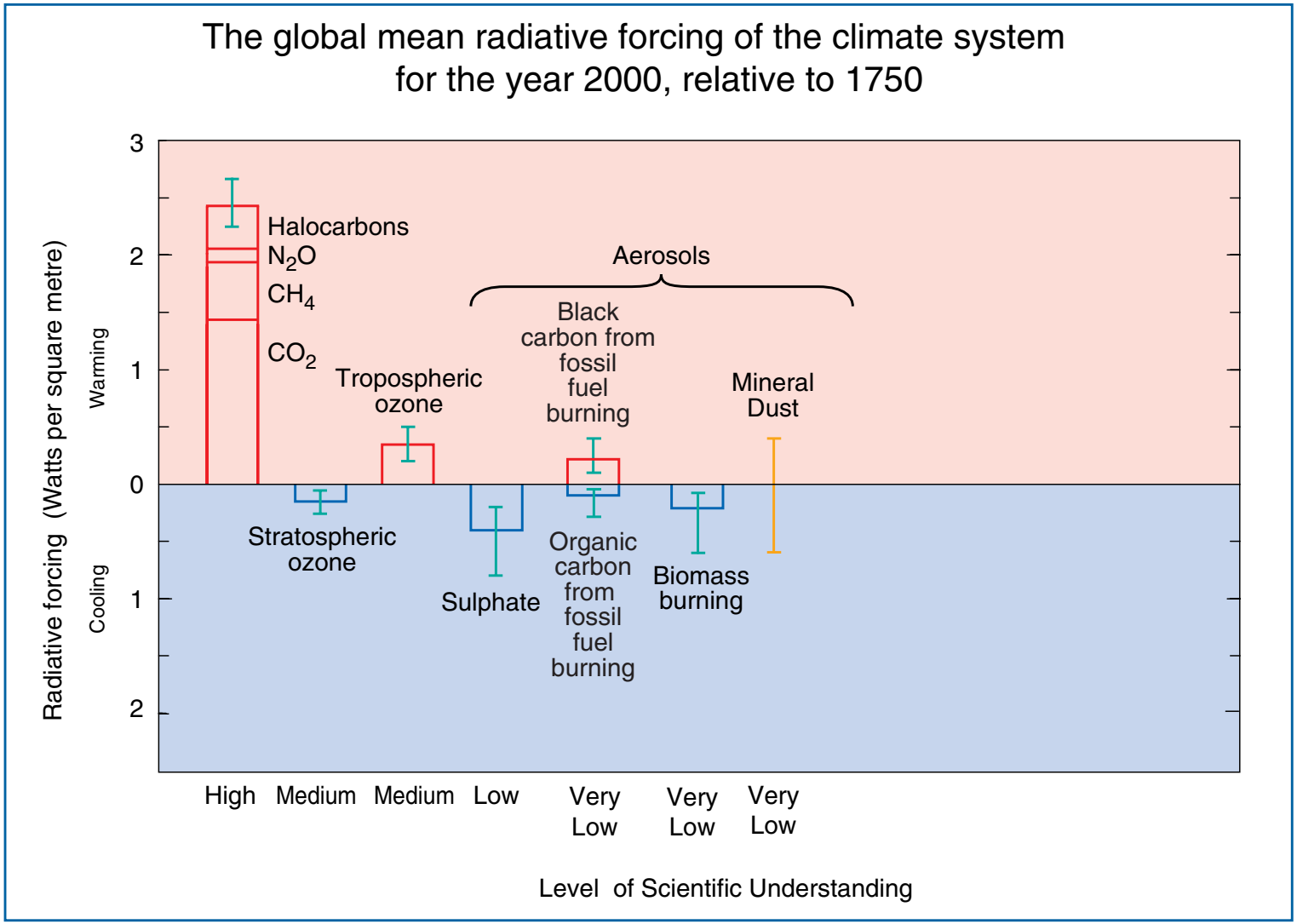

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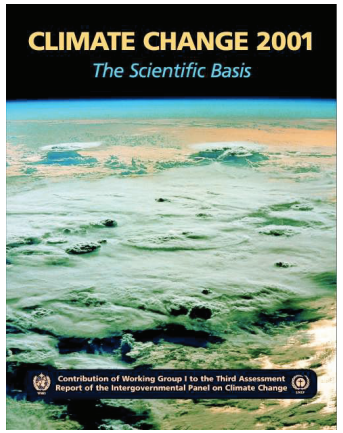
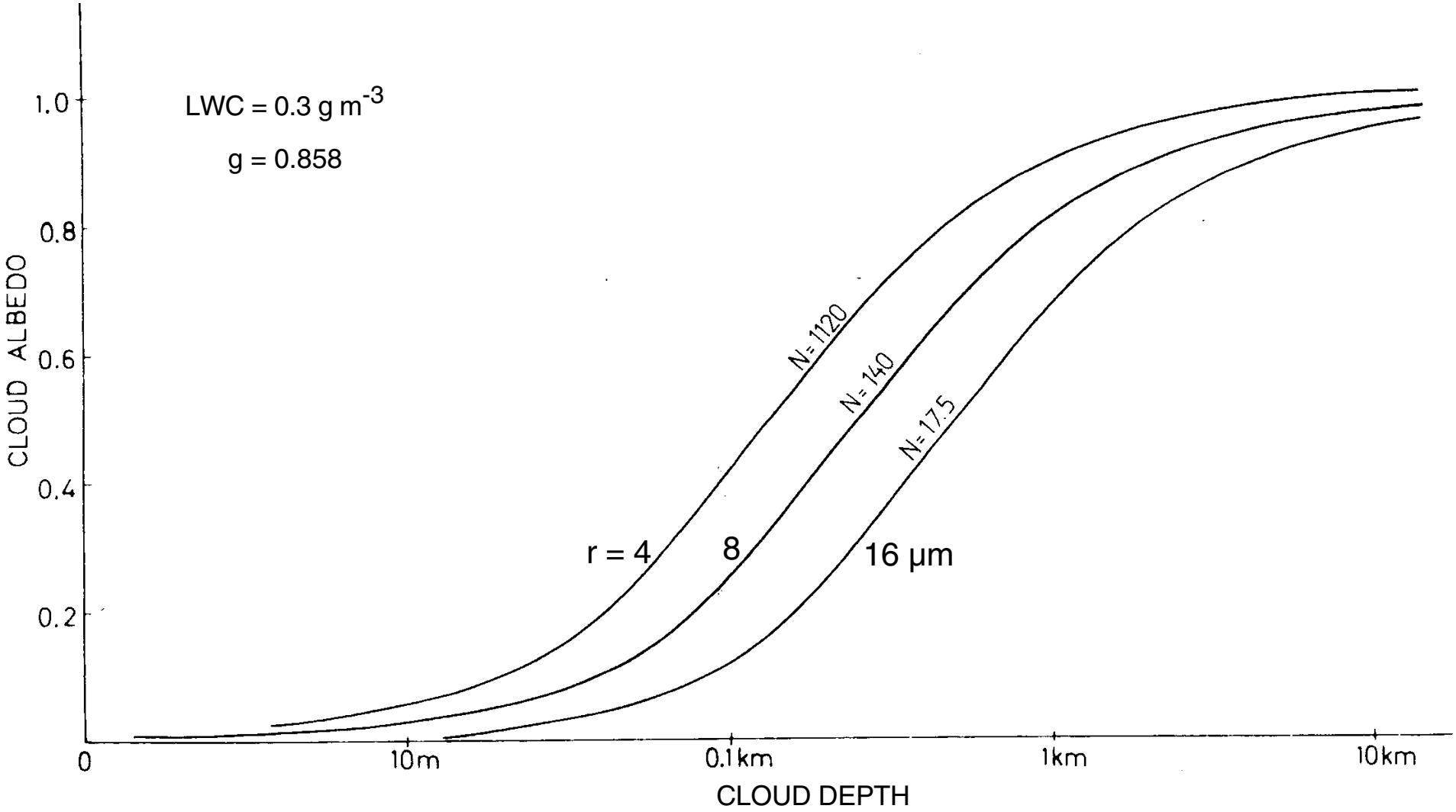


INDIRECT EFFECT

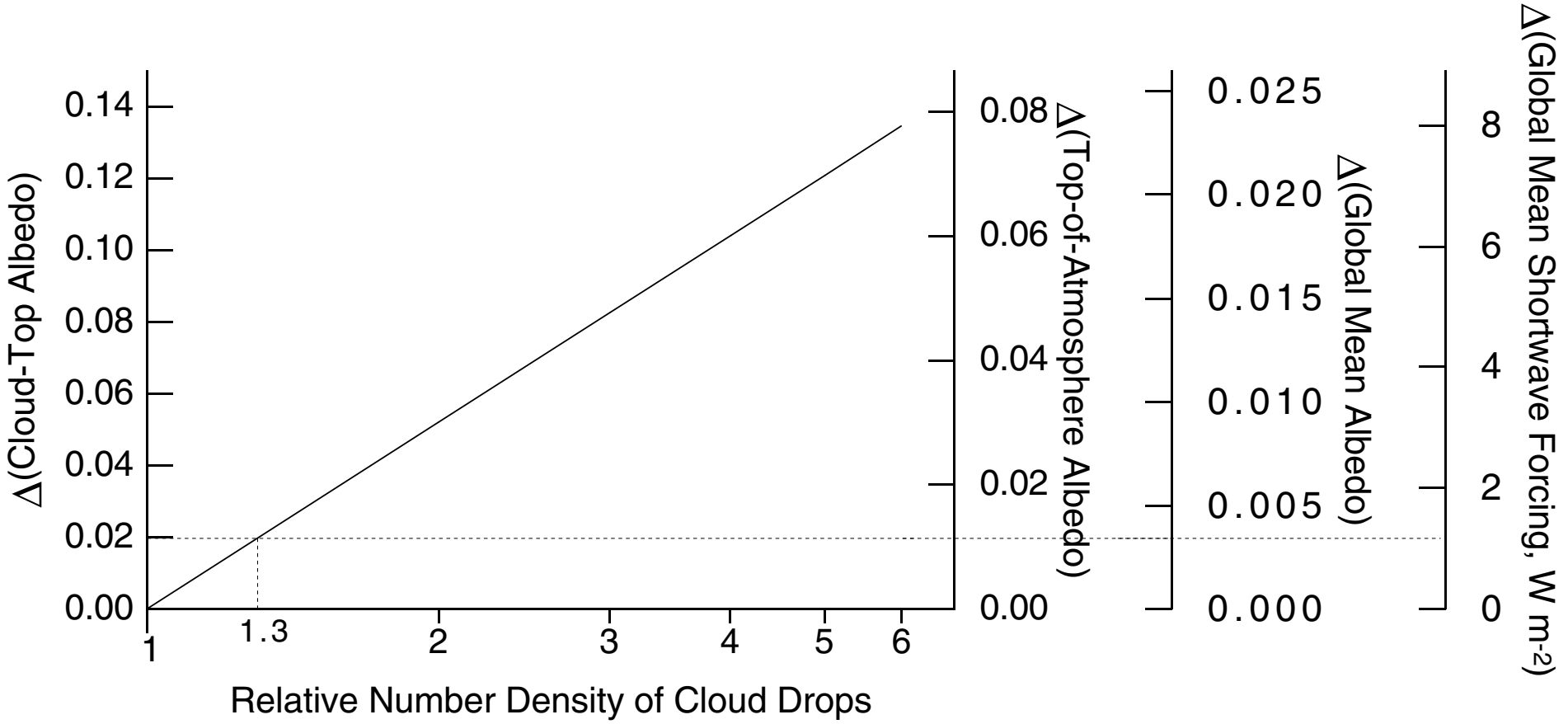
DEPENDENCE OF CLOUD ALBEDO ON CLOUD DEPTH

Influence of Cloud Drop Radius and Concentration



Twomey, *Atmospheric Aerosols*, 1977

SENSITIVITY OF ALBEDO AND FORCING TO CLOUD DROP CONCENTRATION

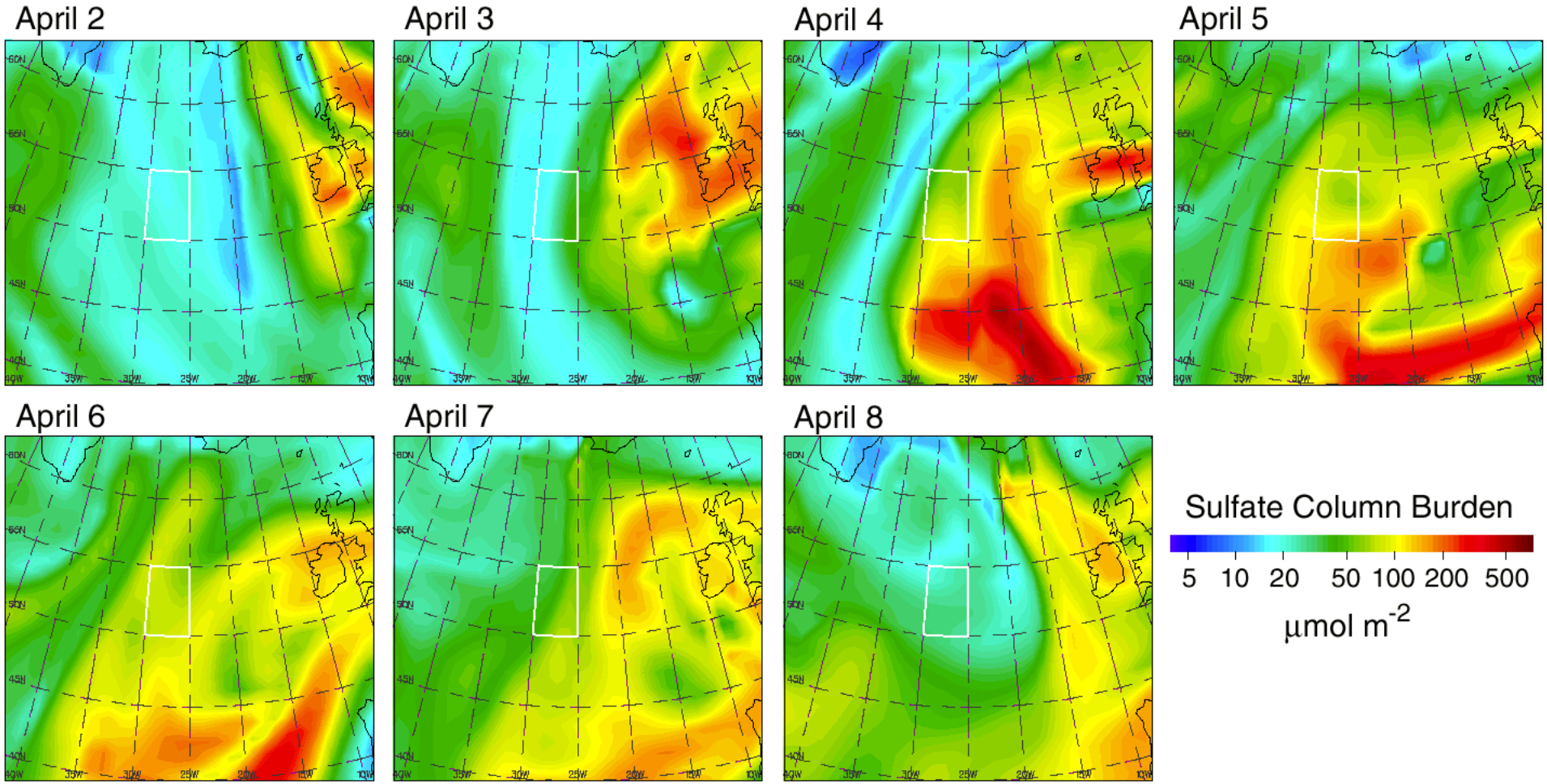


Schwartz and Slingo (1996)

MODELED SULFATE COLUMN BURDEN

$$\int [SO_4^{2-}]dz$$

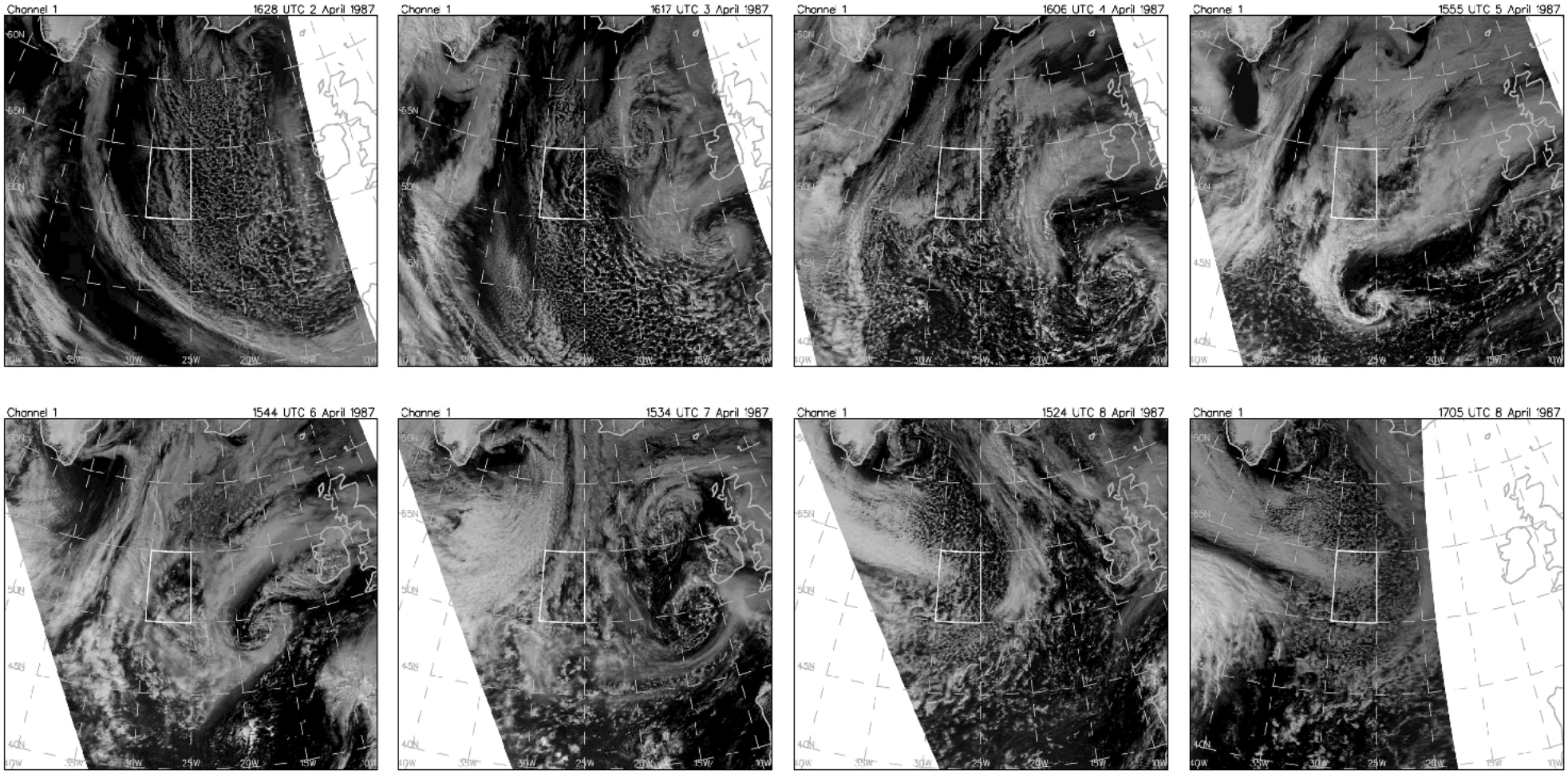
April 2-8, 1987



Schwartz, Harshvardhan &Benkovitz, PNAS, 2002

AVHRR IMAGES APRIL 2-8, 1987

Channel 1, Visible, 0.58-0.68 μm

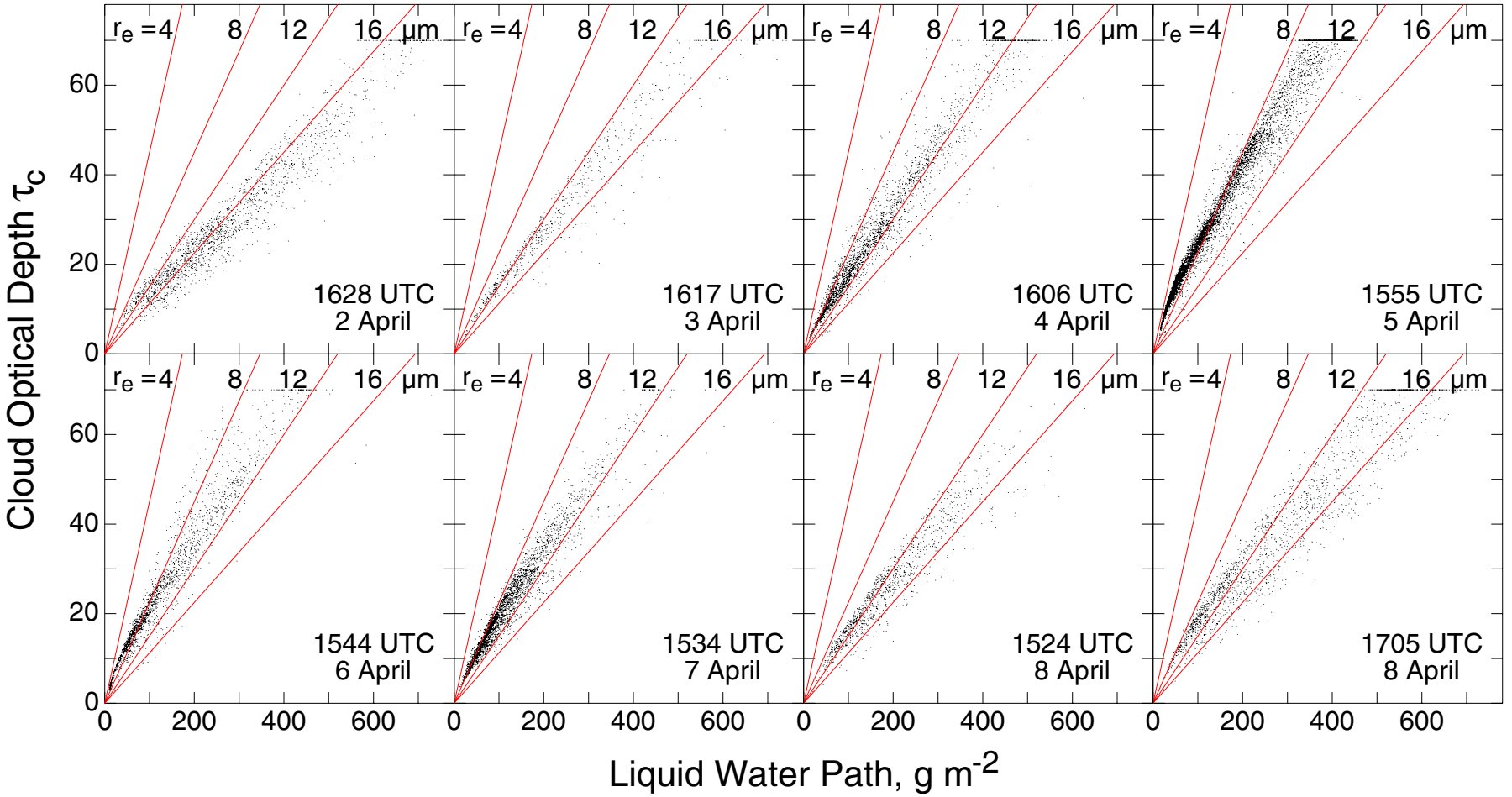


Harshvardhan, Schwartz, Benkovitz and Guo, J Atmos Sci, 2002

CLOUD OPTICAL DEPTH

Dependence on Liquid Water Path

25°-30°W, 50°-55°N April 2-8, 1987

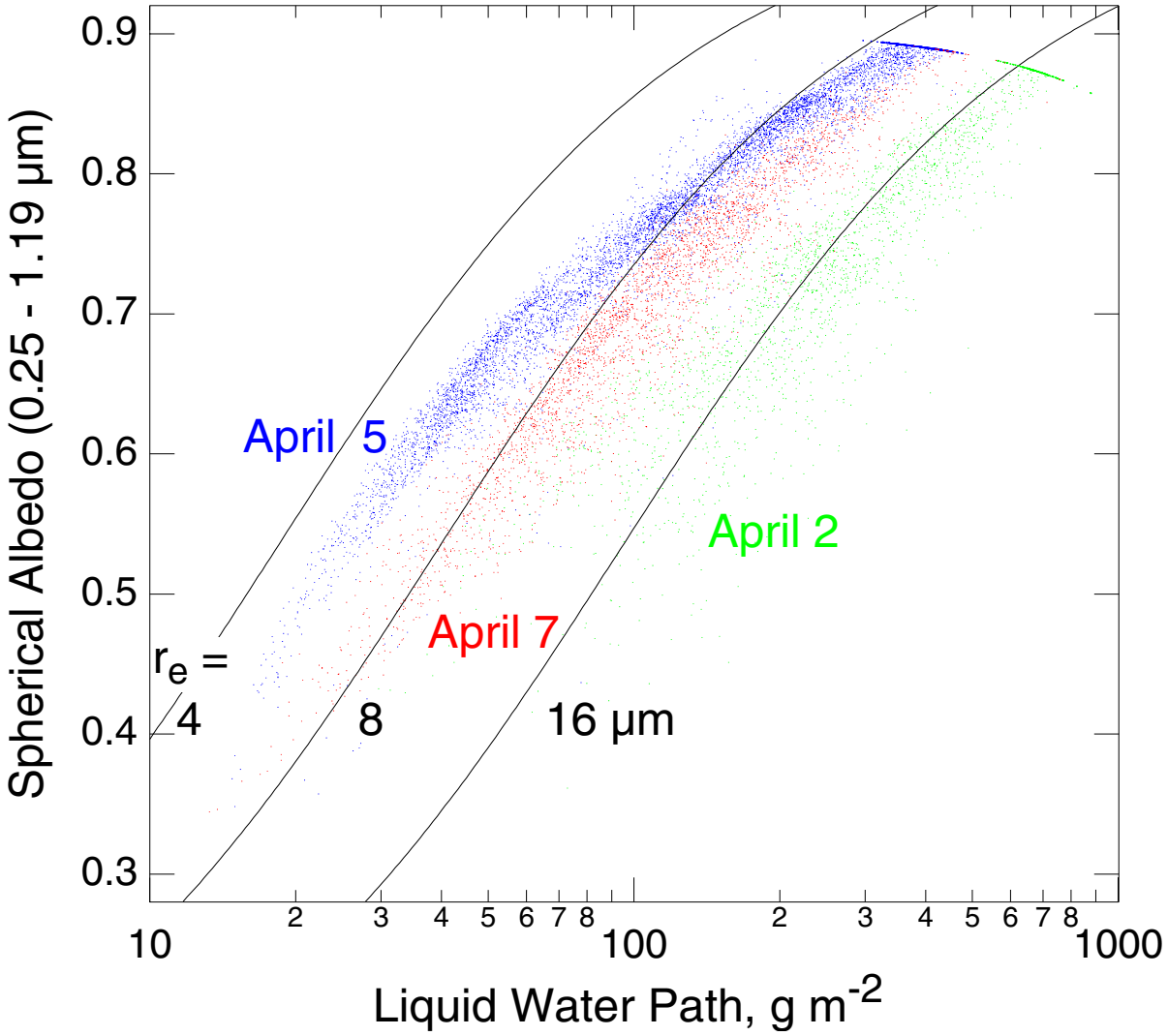


Schwartz, Harshvardhan & Benkovitz, PNAS, 2002

CLOUD-TOP ALBEDO

Dependence on Liquid Water Path

25°-30°W, 50°-55°N April 2, 5 and 7,1987



Schwartz, Harshvardhan & Benkovitz, PNAS, 2002

SULFATE COLUMN BURDEN, CLOUD PROPERTIES AND INDIRECT FORCING

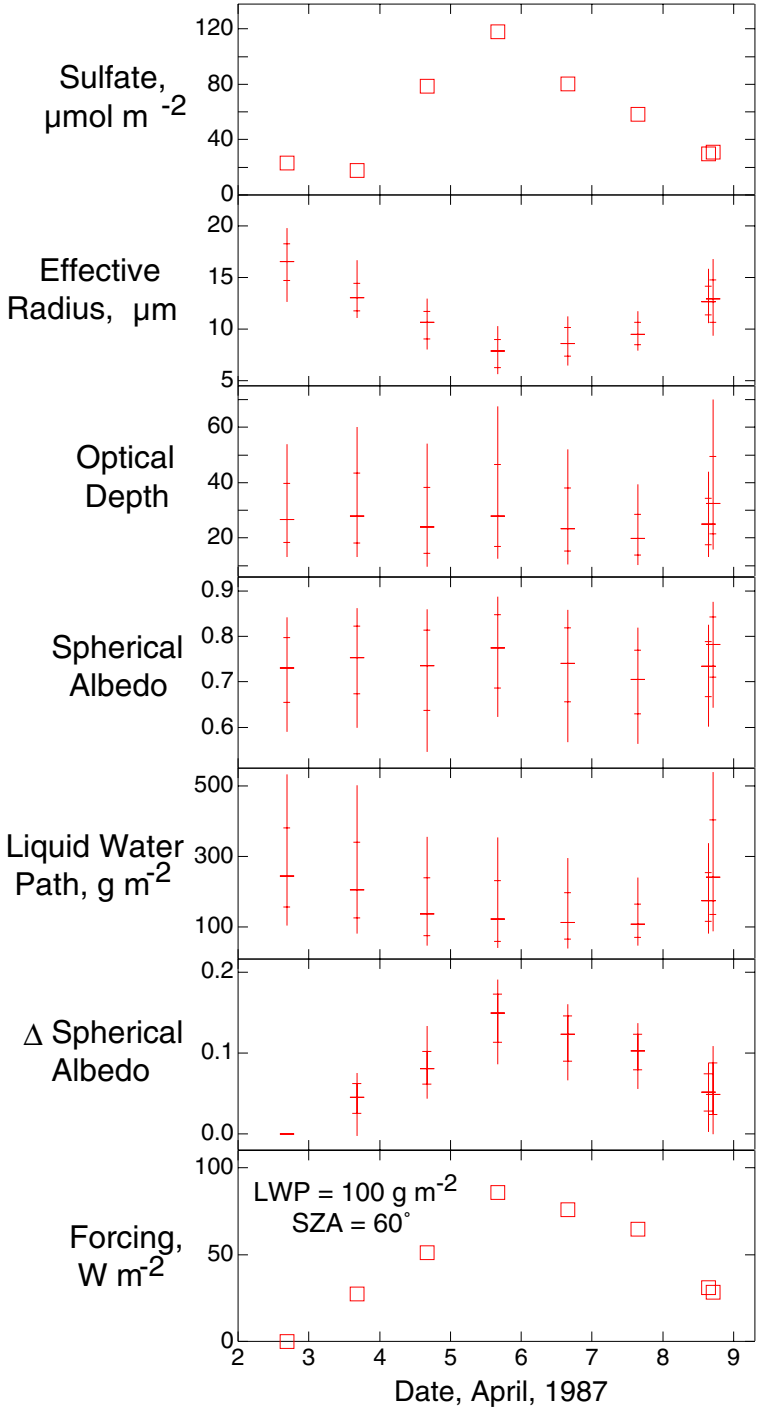
Mid North Atlantic (25-30°W, 50-55°N), April 2-8, 1987

Sulfate from chemical transport model
(Benkovitz et al., *JGR*, 1997)

Cloud drop effective radius and cloud optical depth from satellite retrievals
(Harshvardhan et al., *JAS*, 2002)

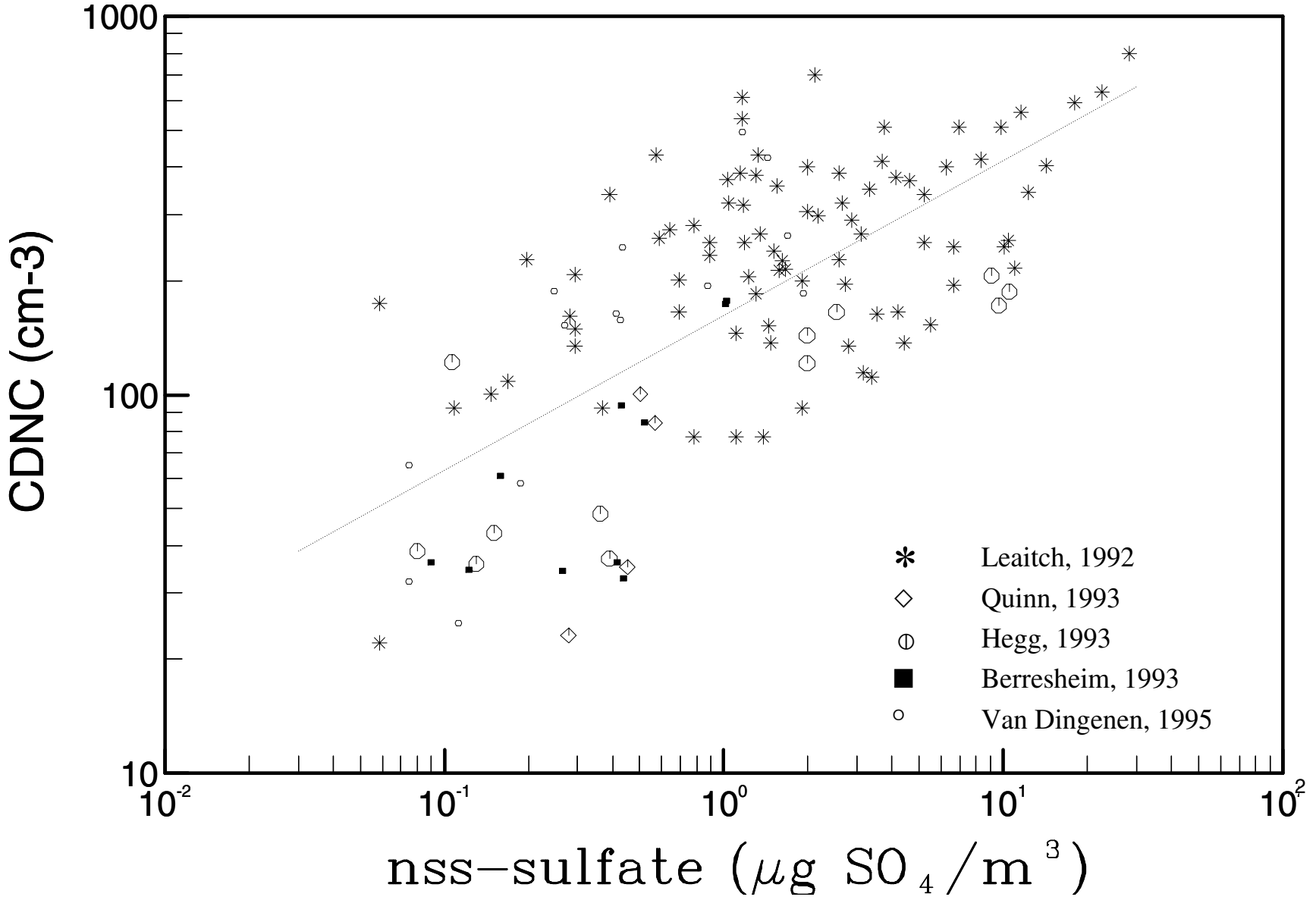
Δ spherical albedo is calculated relative to median effective radius on April 2 (16.5 μm) for retrieved LWP
(Schwartz et al., *PNAS*, 2002)

Forcing is calculated for median effective radius relative to April 2; solar zenith angle 60°; LWP 100 g m^{-2}



CLOUD DROPLET NUMBER CONCENTRATION

Dependence on Non-Seasalt Sulfate

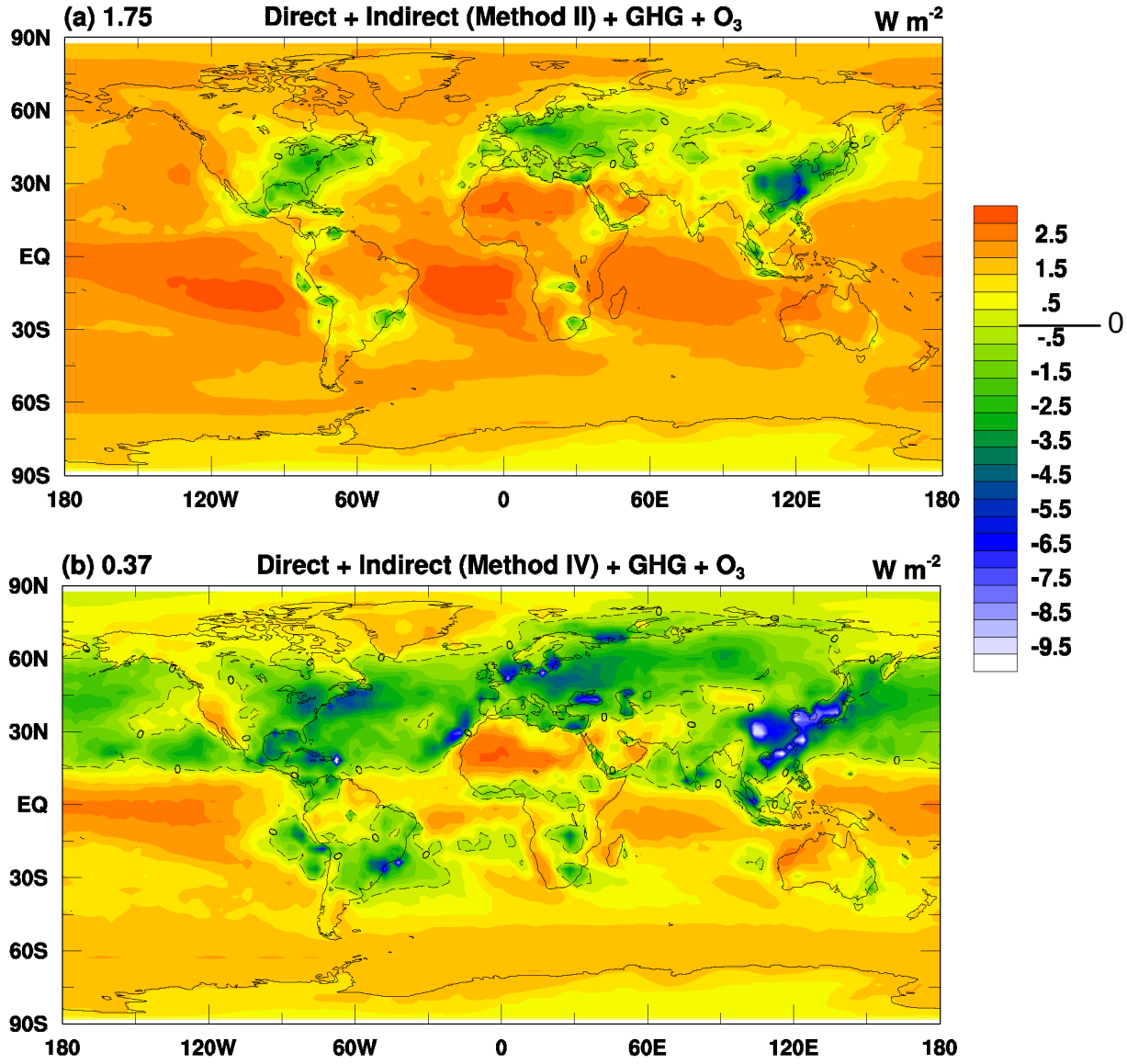


Boucher and Lohmann, 1995

SHORTWAVE FORCING, ANNUAL AVERAGE

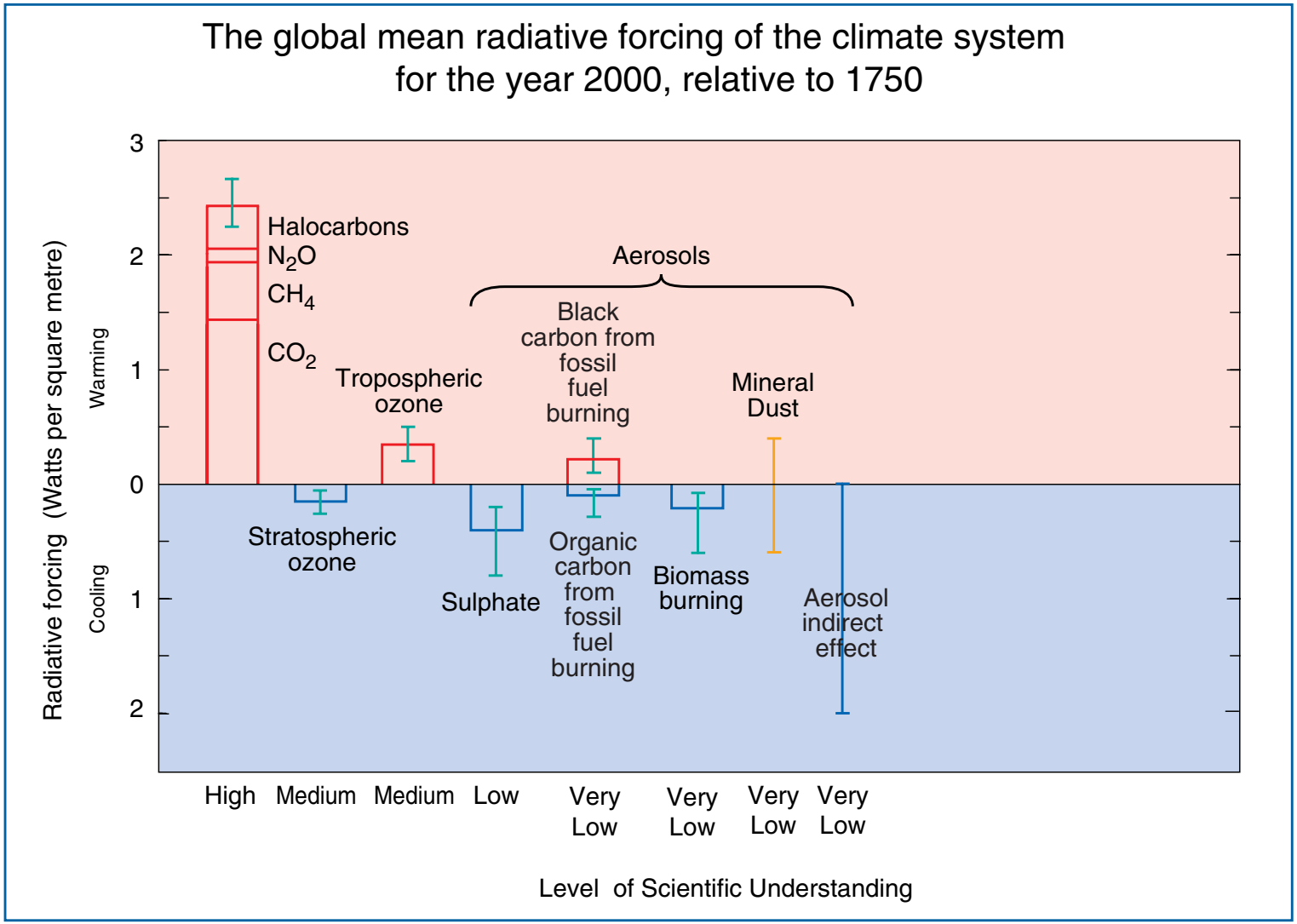
GHG's + O_3 + Sulfate (Direct and Indirect)

Two Formulations of Cloud Droplet Concentration



Kiehl et al., JGR, 2000

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
GHG's and aerosol direct and indirect effects



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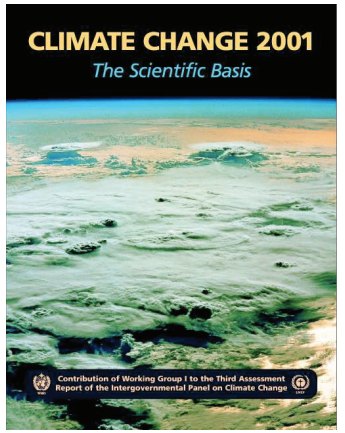


WHY SO LARGE UNCERTAINTY IN AEROSOL FORCING?

- ***Uncertainties in knowledge of atmospheric composition***

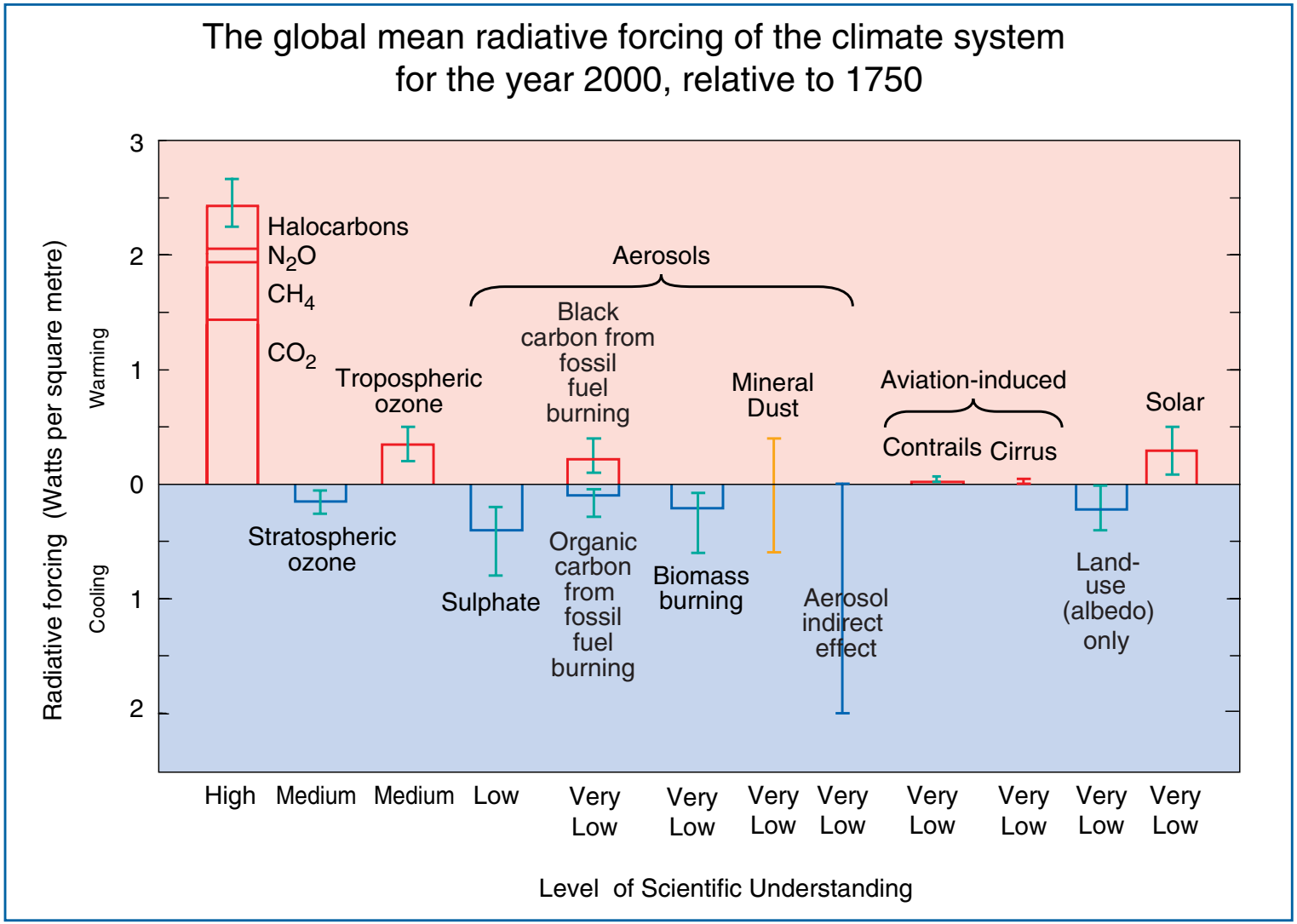
  Mass loading and chemical and microphysical properties and cloud nucleating properties of anthropogenic aerosols, and geographical distribution.

  At present and as a function of secular time.

- ***Uncertainties in knowledge of atmospheric physics of aerosols***

  Relating direct radiative forcing and cloud modification by aerosols to their loading and their chemical and microphysical properties.

RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)



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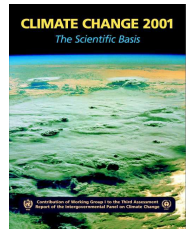
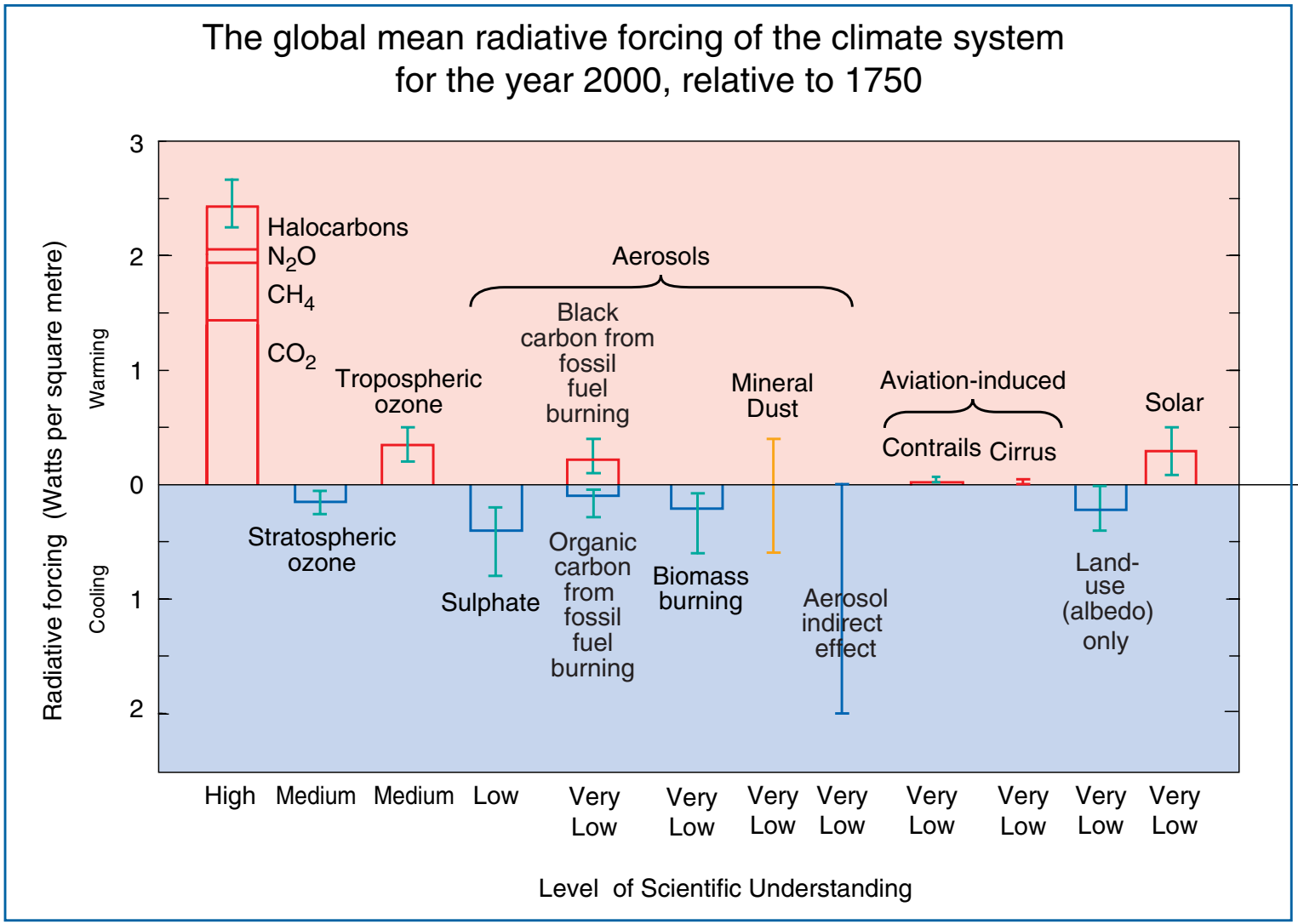
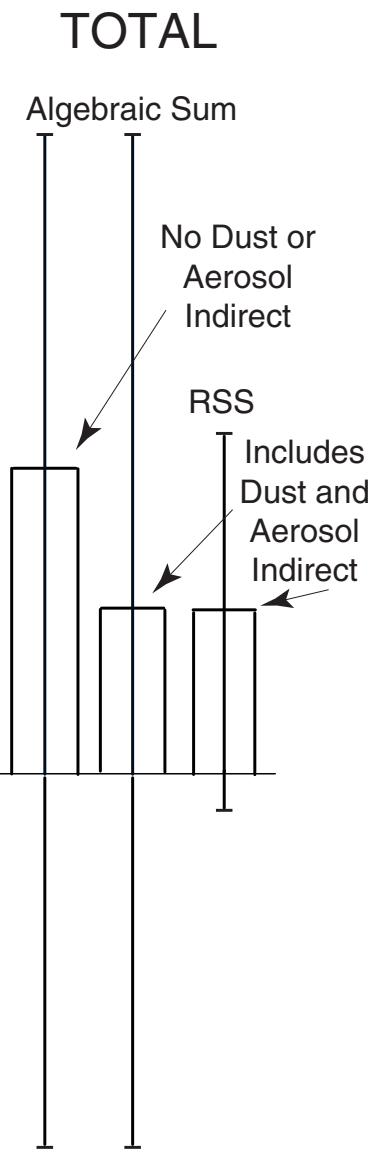


RADIATIVE FORCING OVER THE INDUSTRIAL PERIOD
IPCC (2001)
With totals and overall uncertainties by 3 approaches





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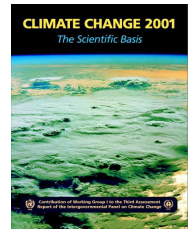
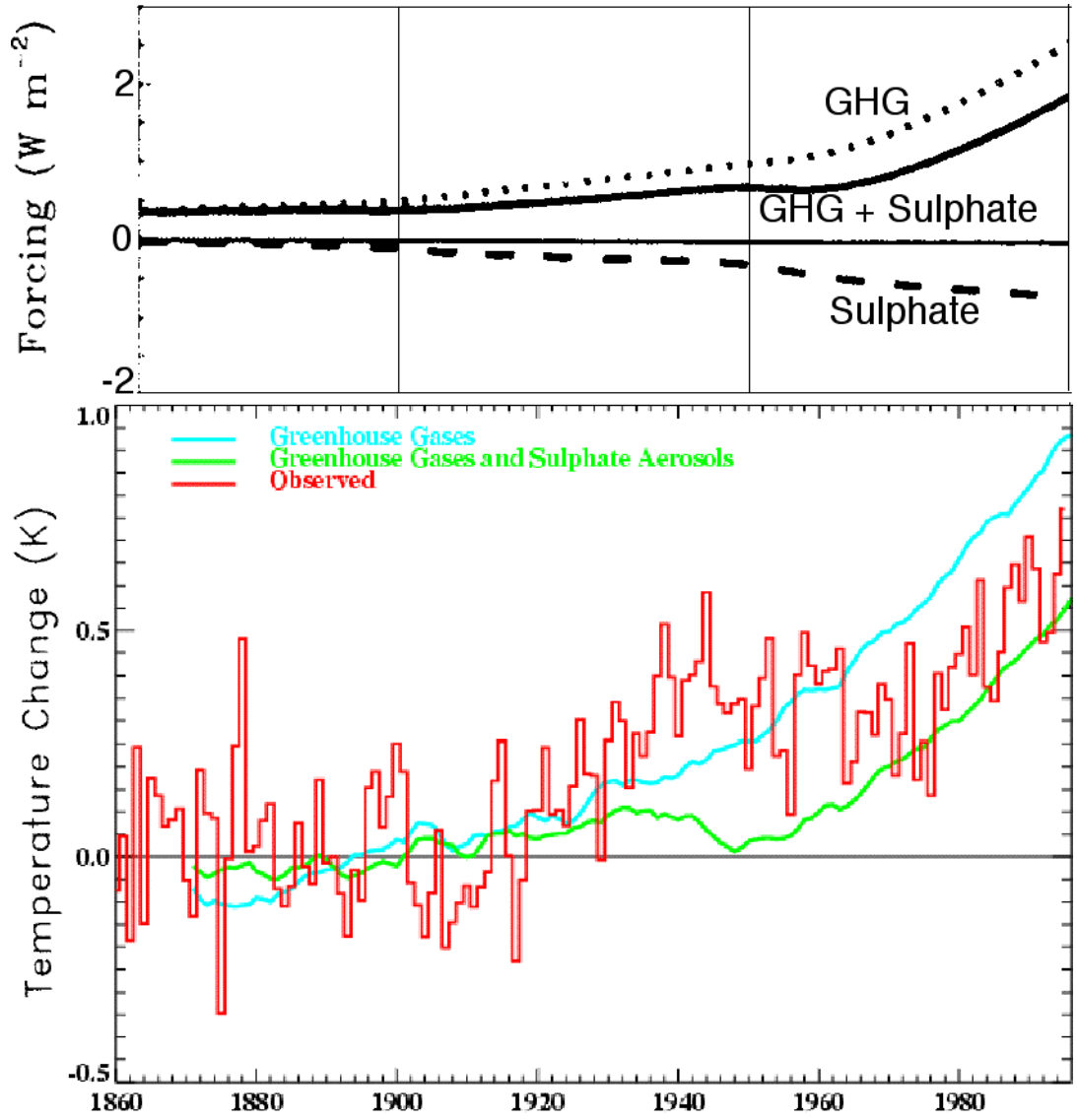


REPRESENTING AEROSOL INFLUENCES IN CLIMATE MODELS

FORCING AND RESPONSE IN THE UK MET OFFICE MODEL (1995)

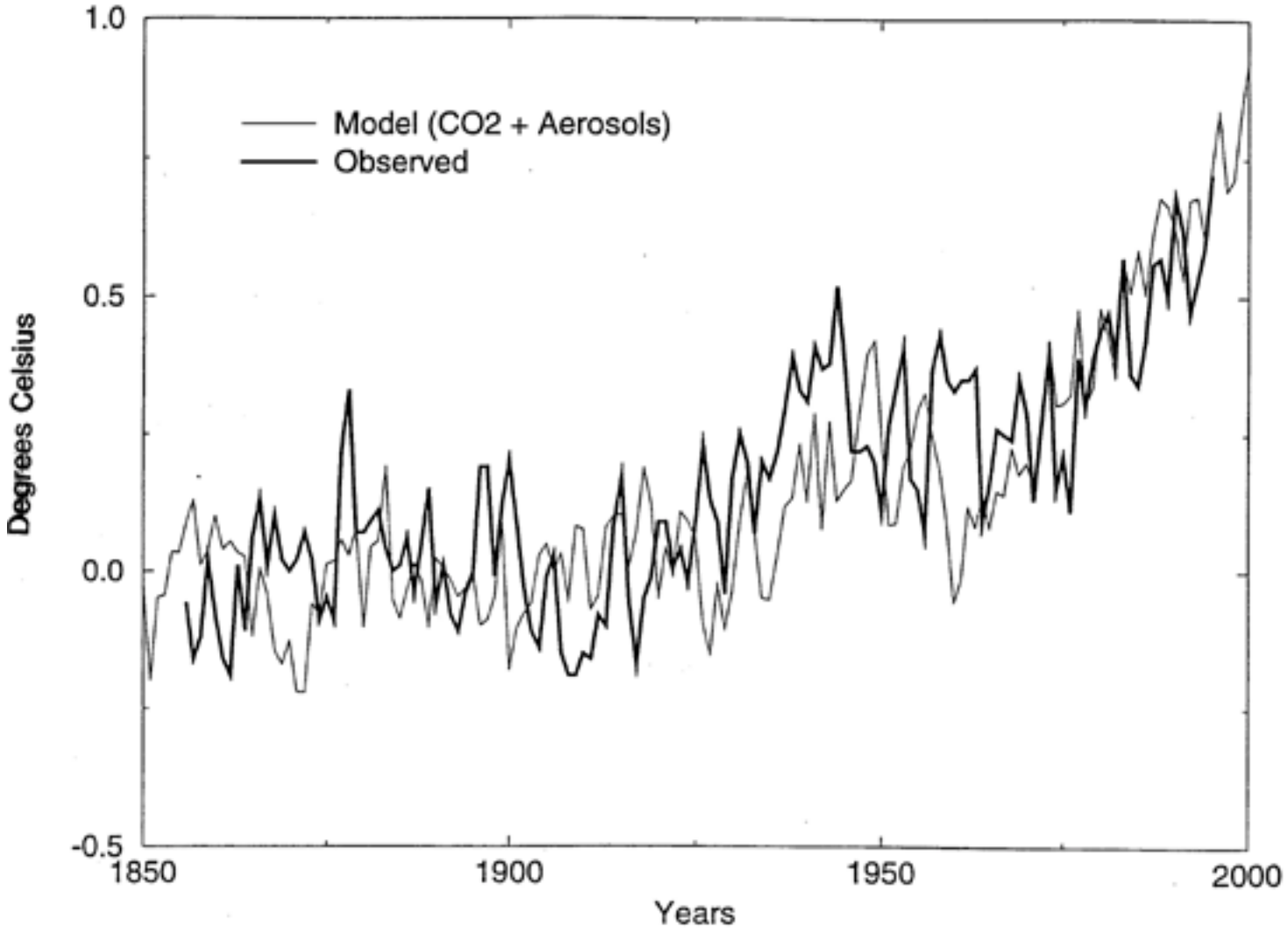
Model sensitivity = 2.5 K per CO_2 doubling; sulfate direct forcing only, -0.6 W m^{-2} (1990)



"Inclusion of sulphate aerosol forcing ***improves the simulation*** of global mean temperature over the last few decades." -- *Mitchell, Tett, et al., Nature, 1995*

CLIMATE RESPONSE IN THE GFDL MODEL (1997)

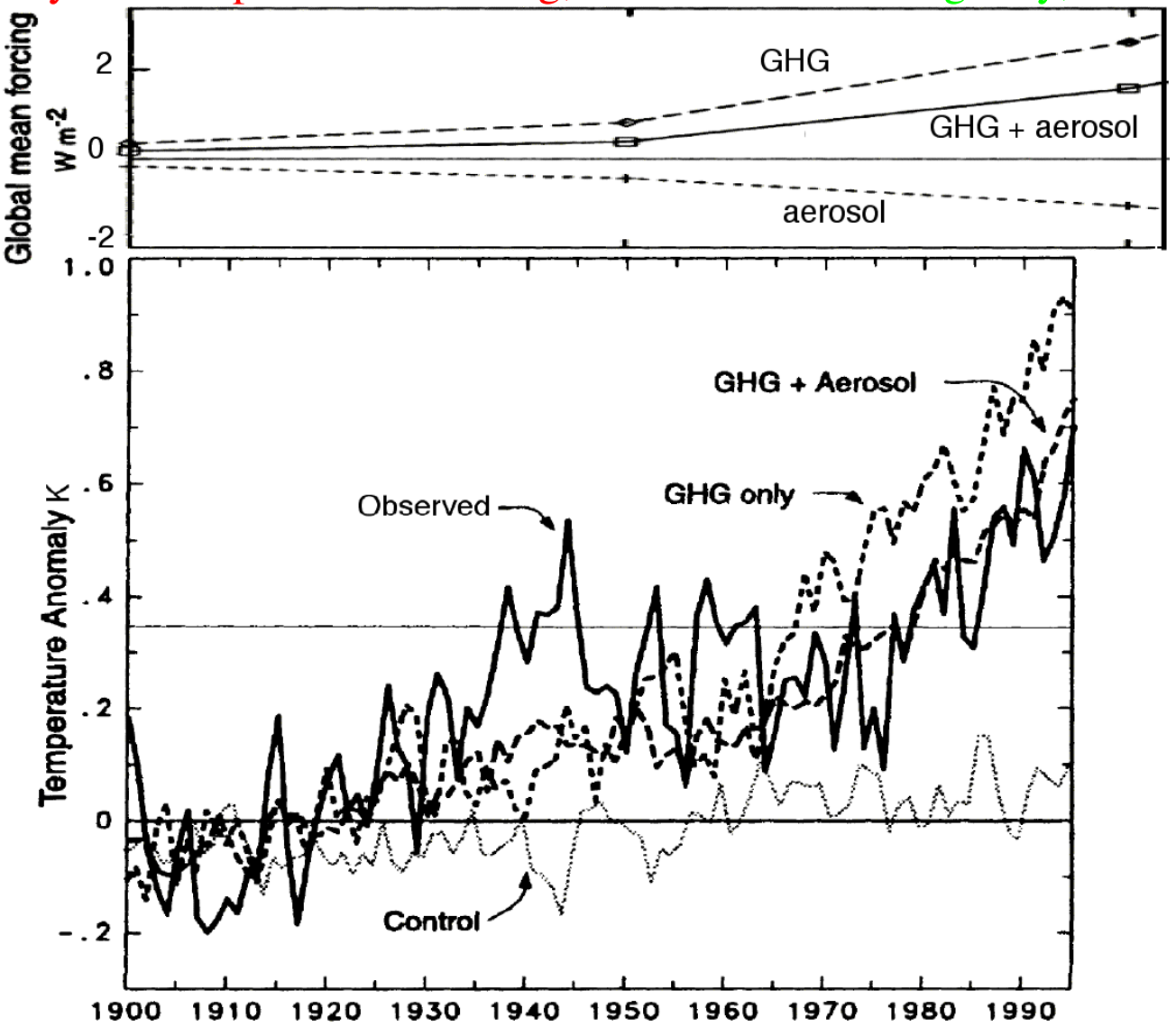
Model sensitivity = 3.7 K per CO_2 doubling; sulfate direct forcing only, -0.6 W m^{-2} (1990)



"The global average SAT trend from the model [is] in ***reasonable agreement*** with the observations." -- *Haywood, Ramaswamy et al., Geophys. Res. Lett, 1997*

FORCING AND RESPONSE IN THE CANADIAN CLIMATE MODEL (2000)

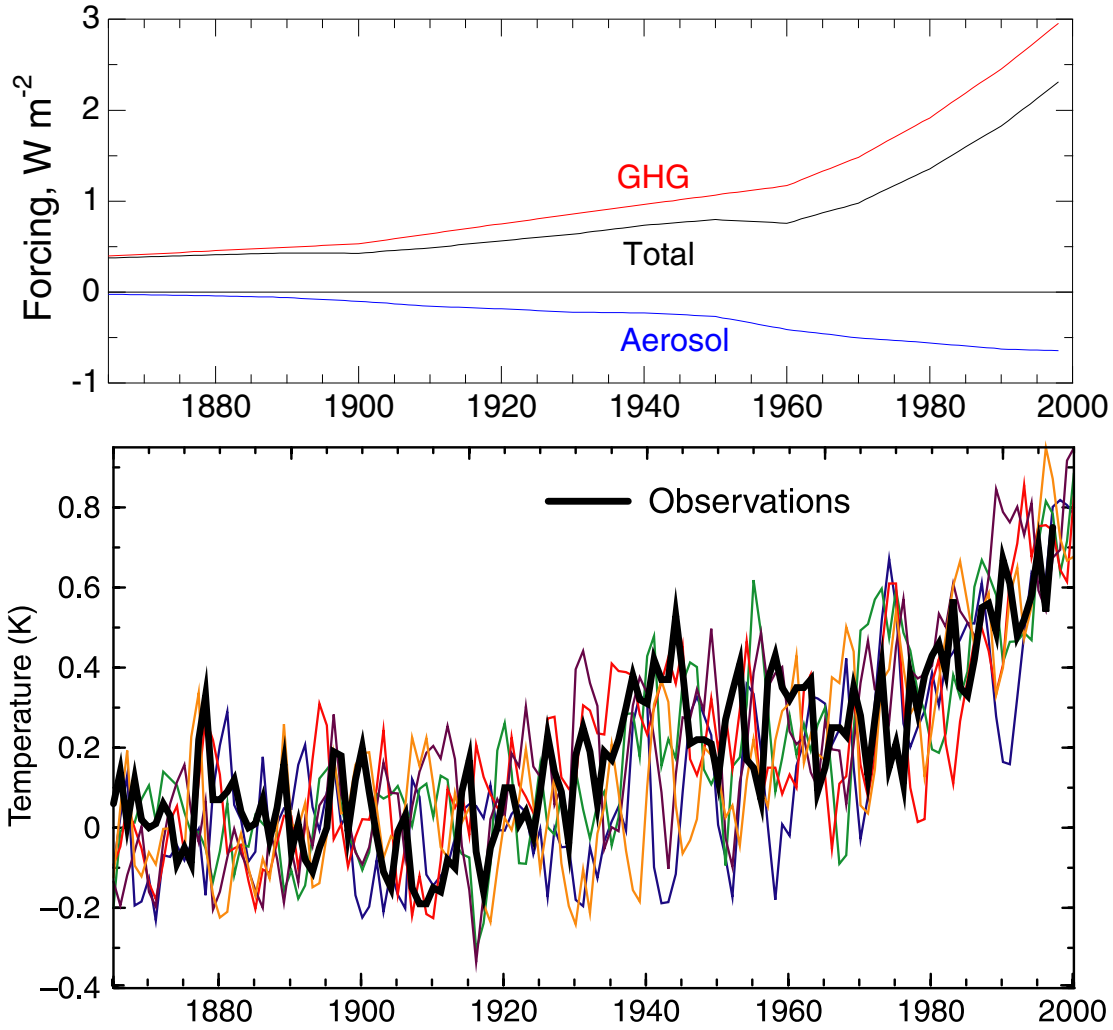
Model sensitivity = 3.5 K per CO_2 doubling; sulfate direct forcing only, -1.0 W m^{-2} (1990)



"Observed global mean temperature changes and those simulated for GHG + aerosol forcing show ***reasonable agreement***." -- *Boer, et al., Climate Dynamics, 2000*

CLIMATE RESPONSE IN THE GFDL MODEL (2000)

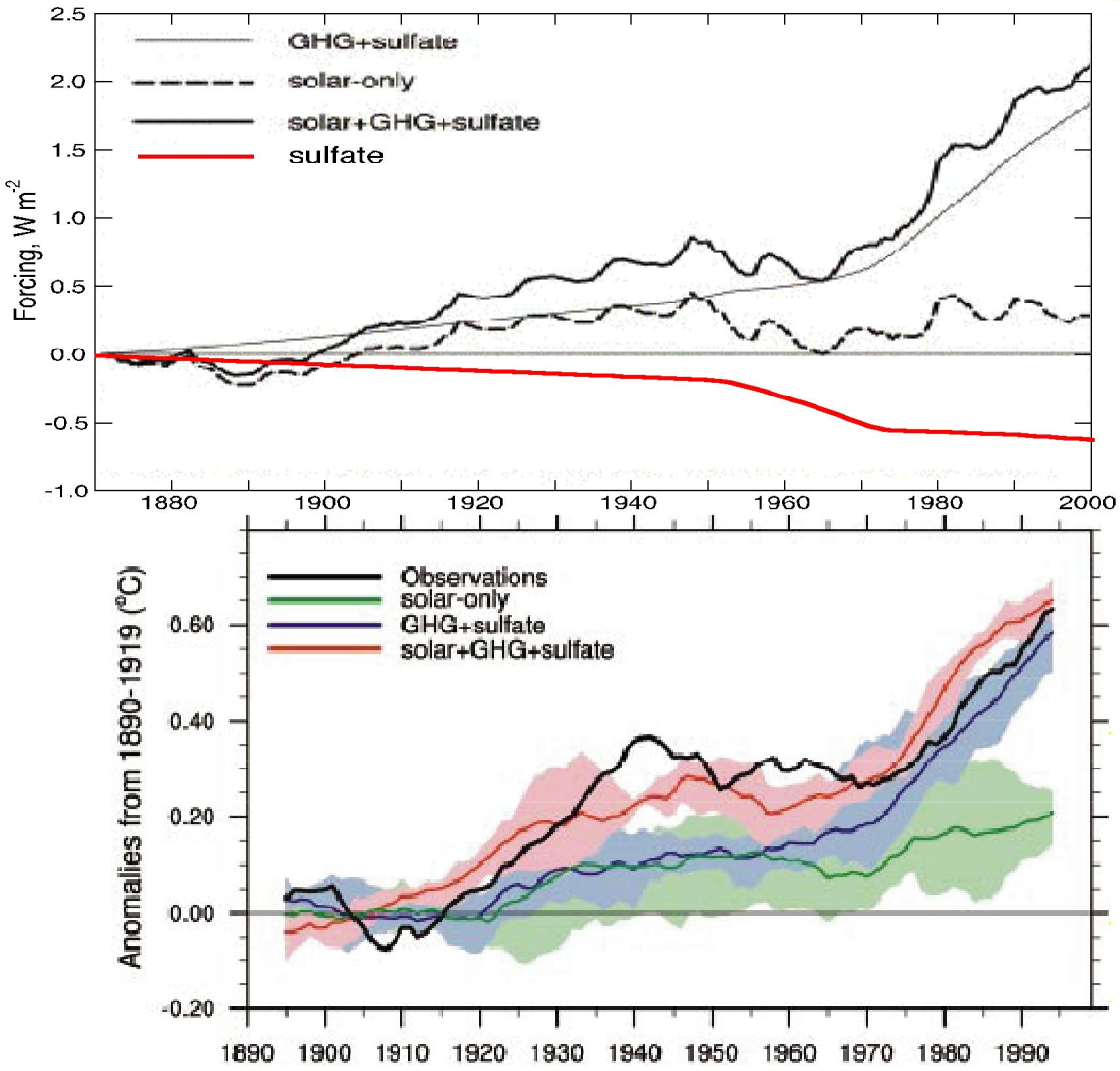
Model sensitivity = 3.4 K per CO_2 doubling; sulfate forcing, -0.62 W m^{-2} (1990)



"The surface temperature time series from the five GHG-plus-sulfate integrations show an increase over the last century, which is ***broadly consistent*** with the observations." -- *Delworth & Knutson, Science, 2000*

FORCING AND RESPONSE IN THE NCAR MODEL (2003)

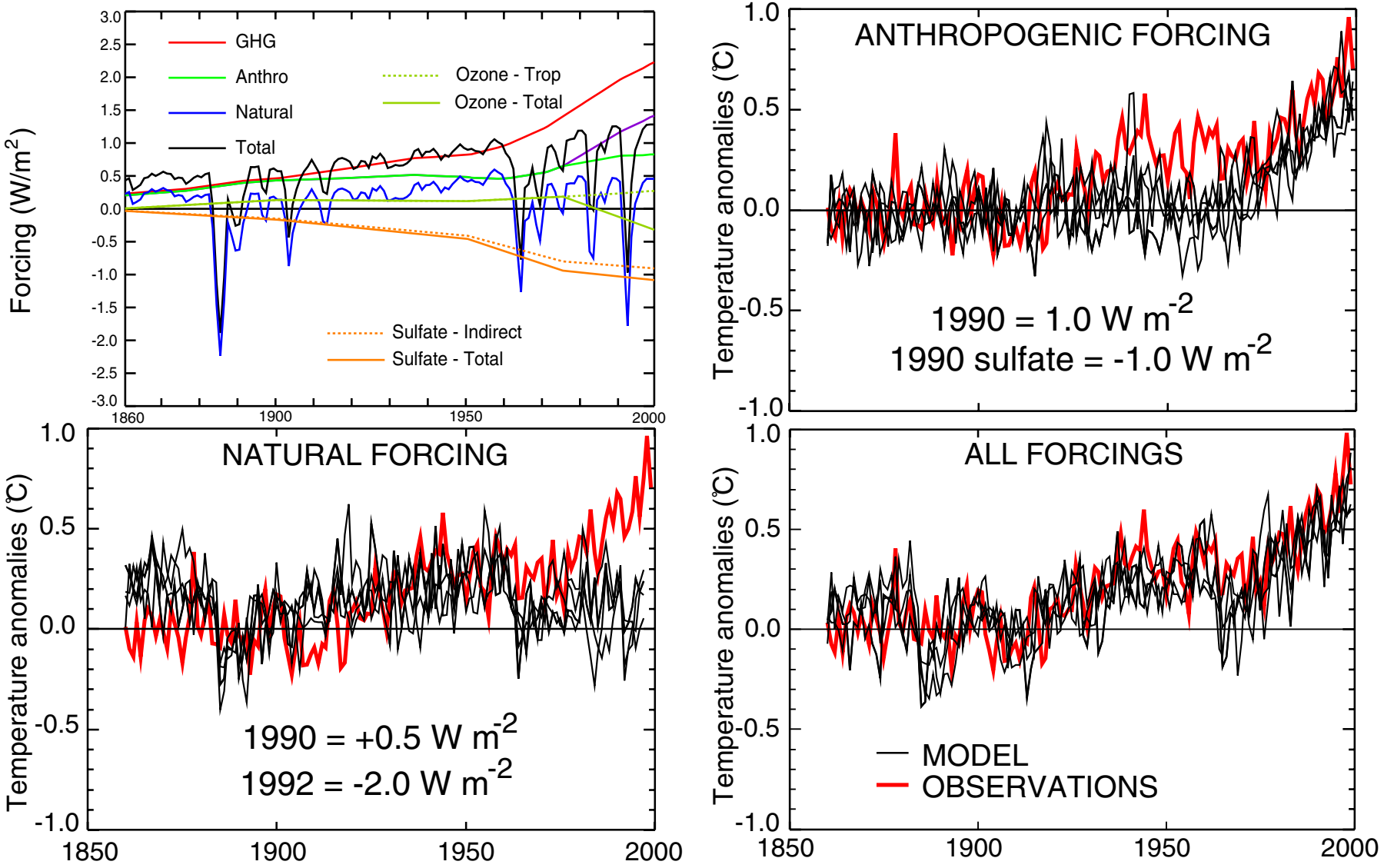
Model sensitivity = 2.18 K per CO_2 doubling; sulfate direct forcing only, -0.6 W m^{-2} (1990)



"The time series from GHG + sulfates + solar shows ***reasonable agreement*** with the observations." -- *Meehl, Washington, Wigley et al., J. Climate, 2003.*

FORCING AND RESPONSE IN THE UK MET OFFICE MODEL (2000)

Model sensitivity = 3.45 K per CO_2 doubling; sulfate + indirect forcing, -1.1 W m^{-2} (1990)

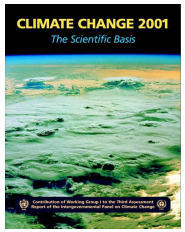


"The ALL ensemble ***captures the main features*** of global mean temperature changes observed since 1860." -- *Stott, Tett, Mitchell, et al., Science, 2000*

IPCC-2001 STATEMENTS ON DETECTION AND ATTRIBUTION OF CLIMATE CHANGE

“ ***Simulations that include estimates of natural and anthropogenic forcing reproduce the observed large-scale changes in surface temperature over the 20th century.***

“ ***Most model estimates that take into account both greenhouse gases and sulphate aerosols are consistent with observations over this period.***




OUR SIMULATIONS THAT INCLUDE ESTIMATES OF NATURAL AND ANTHROPOGENIC FORCING REPRODUCE THE OBSERVED LARGE-SCALE CHANGES IN SURFACE TEMPERATURE OVER THE 20TH CENTURY.
BUT MOM, DON'T THE GCM CALCULATIONS REQUIRE ACCURATE ESTIMATES OF FORCING?
SHHHH!! THE EMPEROR MIGHT HEAR YOU.
IPCC
GCM's
WMO
UNEP
The Emperor's New Clothes

UNCERTAINTY PRINCIPLES

Climate sensitivity $\lambda = \Delta T / F$

The fractional uncertainty in climate sensitivity λ is evaluated from fractional uncertainties in temperature change ΔT and forcing F as:

$$\frac{\delta\lambda}{\lambda} = \sqrt{\left(\frac{\delta\Delta T}{\Delta T}\right)^2 + \left(\frac{\delta F}{F}\right)^2}$$

A reasonable target uncertainty might be:

$$\frac{\delta\lambda}{\lambda} = 30\%, \textit{e.g.,}\ \Delta T_{2\times CO_2} = (3 \pm 1)\ \mathrm{K}$$

This would require uncertainties in temperature anomaly and forcing:

$$\frac{\delta\Delta T}{\Delta T} \approx \frac{\delta F}{F} \approx 20\%.$$

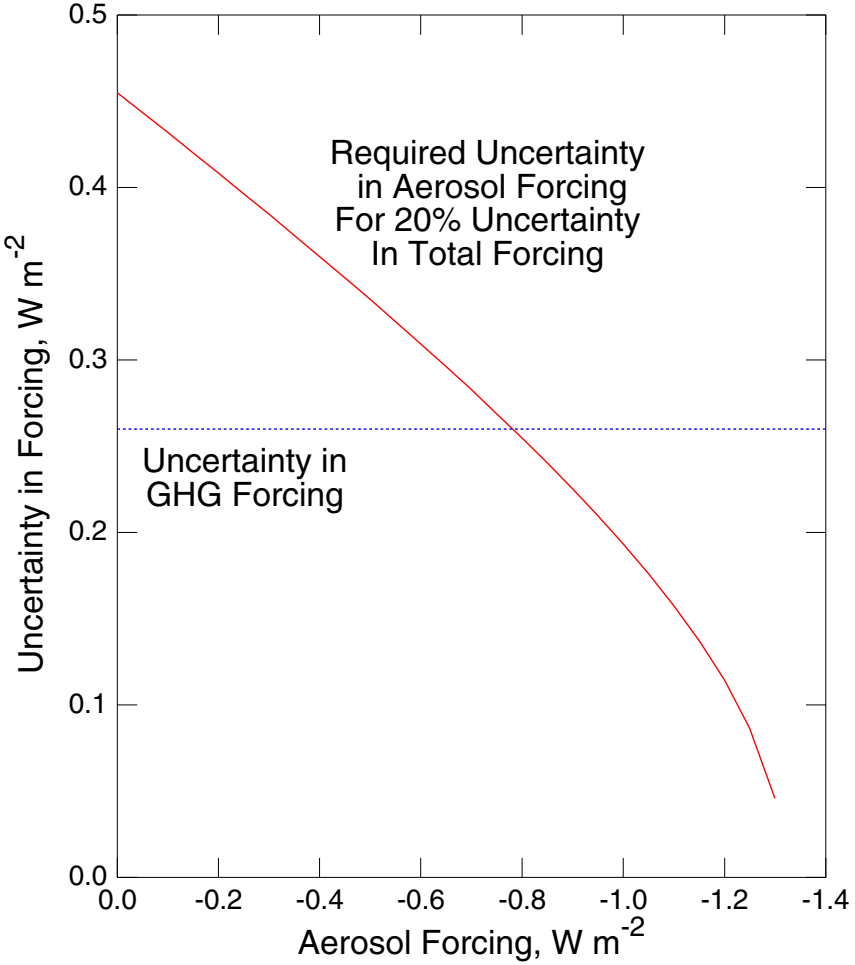
This imposes ***stringent requirements on uncertainty in aerosol forcing!***

REQUIRED UNCERTAINTY IN AEROSOL FORCING

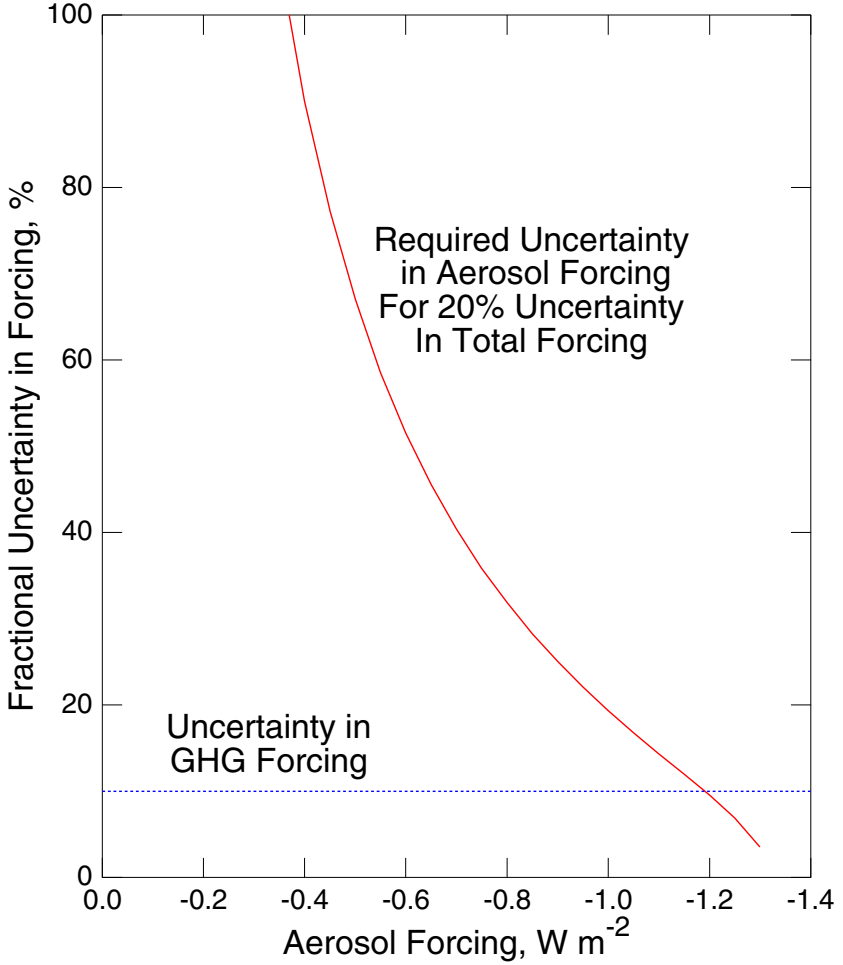
Uncertainty in total forcing not to exceed 20%

GHG Forcing (well mixed gases + strat and trop O_3) = 2.6 W m^{-2} ± 10%

Absolute, W m^{-2}



Percent



KEY REQUIREMENTS FOR FUTURE RESEARCH

- ***Abundance, composition, and mixing state and optical and cloud-nucleating properties of atmospheric aerosols as a function of location and time***

  Observation

  - *In-situ* measurements.
  - Ground-based and satellite-based remote sensing.

  Chemical transport modeling

  - Evaluate by comparison with observation.

- ***Sources of aerosols and aerosol precursors (mass rates and size dependent composition and mixing state)***

  Measurement

  - As a function of location and controlling variables.
  - For anthropogenic *and* natural aerosols.

  Develop emission factors and emission inventories

- ***Atmospheric chemical and microphysical transformation processes***

  Laboratory, theory, field measurements and modeling

cont'd . . .

KEY REQUIREMENTS FOR FUTURE RESEARCH (*cont'd*)

- ***Wet and dry removal processes***
  Size and composition dependence.
- ***Representation of aerosols in chemical transport models***
  Mass loading as a function of location and secular time.
  Size-dependent composition and mixing state.
  - Optical properties
  - Hygroscopic properties
  - Cloud nucleating properties
- ***Aerosol-radiation interactions***
  Quantify aerosol influences on short- and longwave radiation in cloud-free skies.
- ***Aerosol - cloud interactions***
  Quantify the effects of changes in aerosol abundance and composition on cloud formation, persistence, and amount, on precipitation amounts, and on cloud radiative properties.
- ***Uncertainties in all the above***

Thank you!

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http://www.ecd.bnl.gov/steve/schwartz.html